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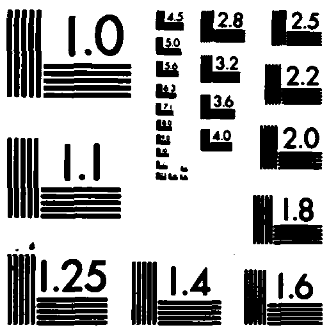

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CONUS Omega/VLF Data Collection: Flight Test

Larry D. King
Edwin D. McConkey

December 1983

Final Report

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16. Abstract

This report contains the description and results of an Omega/VLF flight program conducted in the continental United States (CONUS). The data collection period was during May 1983. The purpose of the program was to collect Omega and VLF signal coverage and accuracy data representative of low altitude, low speed operations typical of helicopters and general aviation aircraft.

The aircraft used was a Beechcraft Queen Air, Model 65. The aircraft was configured with a data collection palate and multipin electrical connectors located in the aircraft cabin. An ARINC 599 type Omega/VLF navigation receiver was used in the project. A flat plate, E-field antenna was mounted in the bottom of the fuselage near the empennage. A microprocessor controlled data collection system, utilizing a scanning DME and other aircraft navigation instruments, was used to record data and establish aircraft reference position.

Route segments, totaling over 7000 nm covering much of CONUS, were flown during the project. Data were recorded on all route segments. Over 7000 data points were used in the accuracy analysis.

The results indicate that adequate signal coverage was available throughout most of the data collection period. Signal coverage was poor during a night flight between Bismarck, ND and Minneapolis/St. Paul, MN in an area where the North Dakota Omega station must be deselected. Navigation errors for the Omega/VLF system exceeded current FAA enroute requirements by 0.9 nm in alongtrack and 0.3 nm in crosstrack. The system was easy to use and did not impose a workload burden on the aircrew.

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METRIC CONVERSION FACTORS

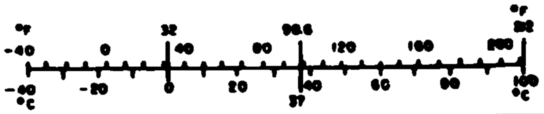
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



60 mph = 52.1 knots (nautical miles per hour)
60 mph = 88'/sec
$1g = 32.2'sec^2$

1 mph = .87 knots
1 knot - 1.15 mph

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1.0 EXECUTIVE SUMMARY

1.1 INTRODUCTION

This report contains a description and results of an Omega/VLF flight project that was conducted in the continental United States (CONUS). The project was performed during May 1983. The purpose was to collect Omega and VLF signal coverage and accuracy data representative of low altitude, low speed operations typical of helicopters and general aviation aircraft.

1.2 DATA COLLECTION EQUIPMENT

The project aircraft was a Beechcraft Queen Air, Model 65. The aircraft was leased by the contractor and configured with a data collection palate and multipin electrical connectors located in the aircraft cabin. The connectors provide 28V DC, 115V/400Hz AC power and signals from several aircraft navigation instruments.

An ARINC 599 type Omega/VLF navigation receiver was used in the project. The equipment consisted of a receiver/processor unit, a control/display unit and an antenna unit. The antenna was a flat plate E-field type that was mounted aft on the bottom of the fuselage. The E-field antenna was selected for the project when skin mapping revealed that the aircraft was too noisy for an H-field antenna. This situation is quite common in helicopters and smaller general aviation aircraft. The control/display unit was located on the aircraft console and was operated by the flight crew during the test. The course deviation signal and a system warning flag were displayed on a conventional, course deviation indicator located on the pilot's flight instruments.

1.3 DATA COLLECTION AREA

Route segments, totaling over 7000 nm and covering much of CONUS, were flown during the project. Specific segments used in the project are listed in Table 1.1. The segment between St. Paul, Minnesota and Dickinson, North Dakota was flown on three occasions at different times of the day and night. The purpose of the three flights was to examine signal coverage and accuracy under differing ionospheric conditions. The region around the North Dakota Omega station was selected for this project activity. This area is considered to have potential signal coverage problems because stations must be deselected when the aircraft is within about 300 nm due to phase errors caused by modal interference. In addition, lines of position in this area from Hawaii, Australia, Washington and Maine are nearly colinear and produce poor fix geometry.

1.4 SIGNAL COVERAGE

Signal data were recorded on a cassette tape recorder mounted in the aircraft cabin. Data included signal numbers and station use information. Signal numbers for the 10.2 kHz and 13.6 kHz Omega frequencies were recorded from all eight stations. Signal numbers

Table 1.1 Flight Test Segments

SEGMENT	ORIGIN	DESTINATION
1	West Palm Beach, FL	Columbia, SC
2	Columbia, SC	Wilmington, DE
3	Wilmington, DE	Flint, MI
4	Flint, MI	Minneapolis/St. Paul, MN
5	Minneapolis/St. Paul, MN	Bismarck, ND
6	Bismarck, ND	Minneapolis/St. Paul, MN
7	Minneapolis/St. Paul, MN	Dickinson, ND
8	Dickinson, ND	Missoula, MT
9	Missoula, MT	Eugene, OR
10	Eugene, OR	Fresno, CA
11	Fresno, CA	Albuquerque, NM
12	Albuquerque, NM	Little Rock, AR
13	Little Rock, AR	Montgomery, AL
14	Montgomery, AL	West Palm Beach, FL

from seven VLF stations used by the receiver were also recorded. The signal numbers vary between 0 and 100 and are directly related to signal to noise ratio (SNRs) for Omega. For the VLF signals, the signal numbers are related to signal-to-noise ratio, but they also depend upon the signal modulation and therefore cannot be directly related to SNR.

Station use data indicates those times when the station is used in the Omega/VLF position solution. Stations were deselected when any of the following conditions applied:

- low signal number
- proximity to the transmitter (less than 300 nm)
- probability of long path signal contamination

  (LaReunion was always deselected and Liberia was deselected when any part of the propagation path was in darkness)

Subsequent analysis of the signal coverage data produced the following results:

- Signal availability was adequate on thirteen of the fourteen flight segments. Signal availability was marginal on the night flight from Bismarck, ND to Minneapolis/St. Paul, MN.

- The E-field antenna worked very well throughout the project and no obvious instances of precipitation static problems were evident even though periods of rain and snow were encountered during the flights. During this time only the Hawaii Omega station and the NPM-Hawaii, NLK-Washington and NAA-Maine VLF stations produced strong signals and were available for navigation. The Australia and Japan Omega stations were received with marginal signal levels and were available during portions of the flight. North Dakota Omega station was received but not used due to proximity to the transmitter. NSS-Maryland VLF station was not transmitting at this time (NSS-Maryland VLF station transmitted only one day during the test).

1.5 NAVIGATION AVAILABILITY AND ACCURACY

Navigation data were recorded on a microprocessor based data collector which stored a number of position related parameters on cassette tape. The following parameters were recorded:

Aircraft Instrument Parameters

- VOR bearing
- DME distance (aircraft DME)
- heading
- altitude
- time (data collector clock)
- course deviation and flag

Reference Aircraft Positioning System

- DME distances (scanning DME)
- co-channel VOR frequency
- time tag (corresponds to time of the distance measurement)

Omega/VLF Navigation Parameters

- distance to waypoint
- desired track
- latitude
- longitude
- Greenwich Mean Time
- signal data

Aircraft position was established during post flight data processing from the multiple DME distance measurements (up to seven per second) provided by the scanning DME. Navigation accuracy was determined by comparing the Omega/VLF position and navigation parameters with corresponding parameters derived from the DME position reference system.

The flights and subsequent analysis of the recorded data produced the following results:

- The overall errors of the Omega/VLF system slightly exceed current Federal Aviation Administration enroute requirements for non-VOR/DME area navigation systems in Advisory Circular 90-45A. The quantative results are shown in Table 1.2. Accuracy was poor on the night flight segment between Bismarck, ND and Minneapolis/St. Paul, MN due to marginal availability and poor fix geometry of the received signals.

- Navigation system availability was very good on most flight segments. Two system outages occured, one near Flint, MI for twelve (12) minutes and one near Fargo, ND for two (2) hours and thirty-nine (39) minutes. The outages are believed to have been caused by loss of synchronization. The reason for this loss of synchronization is unknown at this time. The Omega/VLF system was not able to resume valid navigation in either instance.

- Except for the two system outages, the system performed very well and provided useful enroute navigation information to the flight crew. The crew found the system to be easy to use posing no problems related to cockpit workload.

Table 1.2 Omega/VLF Accuracy
(nautical miles)

Error Quantity	Mean ($\bar{x}$)	Standard Deviation (σ)	$\bar{x} - 2\sigma$	$\bar{x} + 2\sigma$	AC 90-45A Requirements
Total System Crosstrack	0.17	1.25	-2.33	2.67	2.50
Total System Alongtrack	-0.63	0.89	-2.41	1.15	1.50

2.0 DESCRIPTION AND PROCEDURES

2.1 PURPOSE OF THE DATA COLLECTION

The purpose of the project was to collect Omega/VLF data and develop error budgets which emphasize low altitude operations typical of general aviation aircraft and helicopters. Enroute data was collected across the continental United States (CONUS) "touching" as many of the 48 contiguous states as possible. Over 7000 nm were flown and more than 50 hours of Omega/VLF data were collected. The data collection period was from 9 May 1983 to 17 May 1983.

Navigation system errors (NAT and NCT: navigation error in alongtrack and crosstrack coordinates) were quantified for the ARINC 599 Omega/VLF system tested. The navigation system errors were computed from knowledge of position calculated from the DME tracking data (total system crosstrack error) and the indicated position of the navigator. Total system crosstrack error (TSCT) is defined as the deviation of the aircraft from the desired track (in the crosstrack direction) as measured by the ground truth tracking system. Signal coverage, bias and flight technical error data were collected for position analysis obtained from a multilateration ground truth and data acquisition system carried aboard the test aircraft. Included in the project were equipment checkout and familization flights. Data were collected in a format compatible with analysis requirements as described in Section 4.0

2.2 OBJECTIVES

The objective of this project was to collect and analyze Omega/VLF performance data in the CONUS enroute structure. The specific objectives were defined as follows:

- Collect data relating to signal coverage and navigation system accuracy in the CONUS enroute structure for Omega/VLF.

- Collect and analyze Omega/VLF error budget data in those sections of the 48 contiguous states where there was a lack of such data.

- Collect and analyze signal errors such as propagation errors, signal-to-noise ratios, day/night signal propagation errors, etc.

- Qualitatively evaluate the potential for and the effects of blunders using the Omega/VLF airborne system selected.

- Collect and analyze Flight Technical Error (FTE) data associated with the airborne Omega/VLF system selected.

2.3 LOCATIONS AND PROCEDURES

The extensive navigation coverage provided by a limited number of transmitters made test location a complex process in the case of the Omega/VLF navigation system. System errors and even coverage can vary from location to location depending on such factors as local topography, transmitter geometry and localized electromagnetic disturbances. Locations were chosen to include as many geographically diverse situations as possible within the constraints of the project. For the purposes of this flight, a primary series of 12 flight legs were included*. Average length of a leg was approximately 587 nm. The Omega/VLF airborne system was flown over a 7041 nm route in the continental United States.

In order to decrease the number of ATC directed course deviations, all enroute segments followed the Victor airway structure. Accuracy data were collected whenever the ground truth system was operational (minimum of three DME stations being received with satisfactory geometry) and planned flight altitudes were chosen to maximize line of sight DME reception.

The overall route of flight, as depicted in Figure 2.1, consisted of an area roughly defined by West Palm Beach, FL; Buffalo, NY; Bismarck, ND; Eugene, OR; Fresno, CA; Albuquerque, NM; Montgomery, AL and West Palm Beach, FL. Segments were identified by a number as shown in Table 2.1.

Table 2.1 Omega/VLF Flight Segments

SEGMENT	ORIGIN	DESTINATION	LENGTH (NM)
1	West Palm Beach, FL	Columbia, SC	458
2	Columbia, SC	Wilmington, DE	467
3	Wilmington, DE	Flint, MI	555
4	Flint, MI	Minneapolis/St. Paul, MN	444
5	Minneapolis/St. Paul, MN	Dickinson, ND	447*
6	Dickinson, ND	Missoula, MT	494
7	Missoula, MT	Eugene, OR	466
8	Eugene, OR	Fresno, CA	483
9	Fresno, CA	Albuquerque, NM	714
10	Albuquerque, NM	Little Rock, AR	755
11	Little Rock, AR	Montgomery, AL	381
12	Montgomery, AL	West Palm Beach, FL	483
		Total	7041

/NOTE/: *Segment 5 from Minneapolis/St. Paul, MN to Dickinson, ND was flown a total of 3 times for reasons stated later in the report.

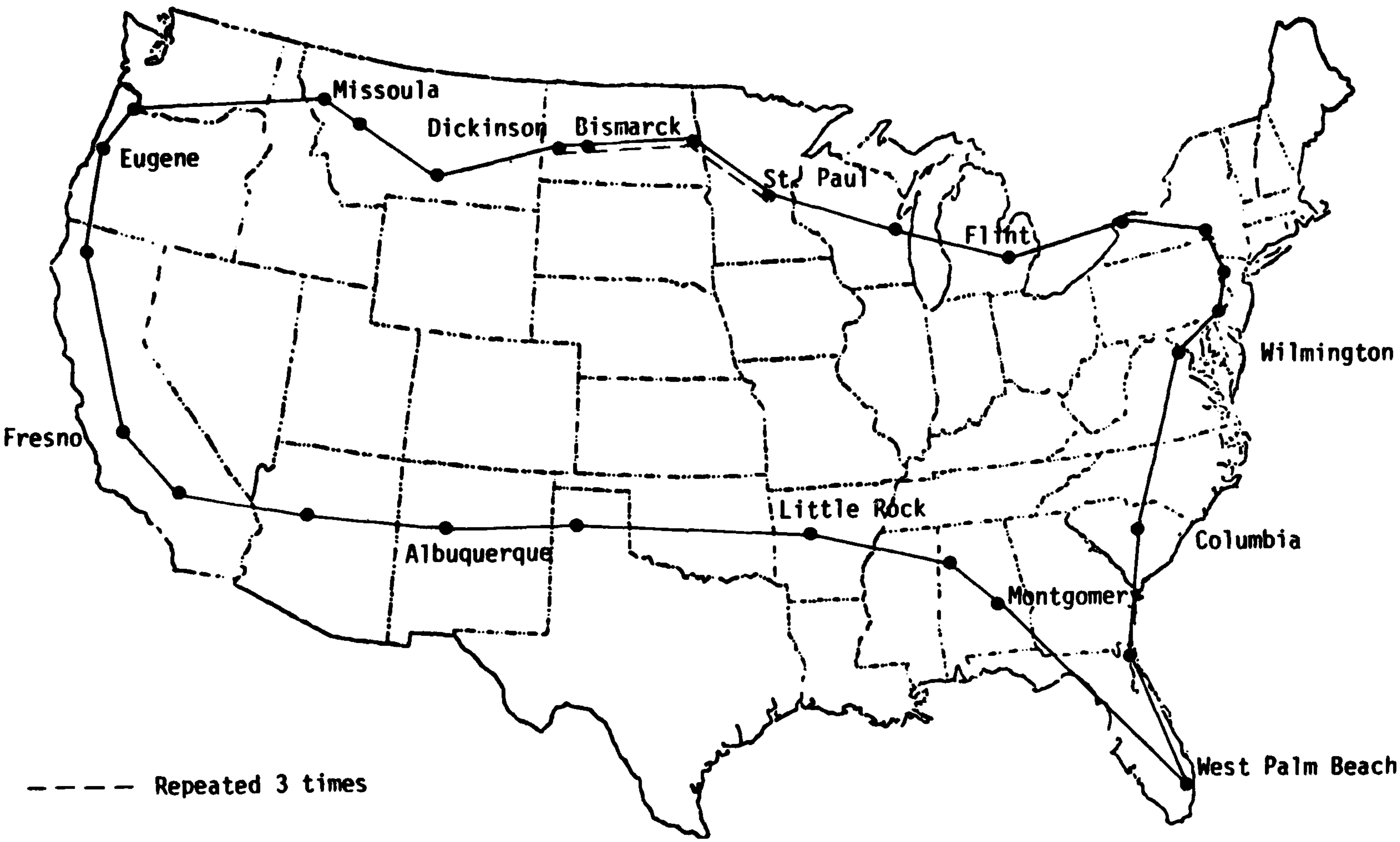

Figure 2.1 Omega/VLF Flight Test Route

Enroute segments included water, coastal plain, central plain and Rocky Mountain overflight. Availability of DME transponders along the route was adequate for data acquisition at flight altitudes in the range of 10,000 - 12,000 feet. One exception to this generality was Segment 6 where a limited number of DME transmitters in western North Dakota and eastern Montana required enroute altitudes above 12,000 feet in order to have adequate data acquisition coverage.

In addition to the requirements of the ground truth system, wide area coverage navigation system considerations also contributed to the development of the flight route. Although Omega signals are intended to be propagated world-wide and thus were theoretically not range limited, they do suffer from several anomalies such as spatial phase instability due to modal interference and day/night changes in the ionosphere.

Segment 5, the leg from Minneapolis/St. Paul, MN to Dickinson, ND, was flown at three different times of the day (morning, afternoon and night) so that possible propagation delay factors caused by day/night effects could be determined. In addition, Segment 5 provided an opportunity to sample the navigation effects of flying in the vicinity of the Omega station located at La Moure, ND, where this station must be deselected due to modal interference.

Accuracy data were collected at all times during enroute operations and were analyzed as to project applicability during the analysis phase by reference to the inflight log maintained by the observer. The data collected during this flight represented a comprehensive baseline data base of both FTE and navigation system error values over a variety of topographic and geographic conditions. Collection of enroute data was generally straightforward with little or no DME reception difficulties encountered.

2.4 FLIGHT CREW

Two subject pilots were utilized for this effort. Both pilots were commercial and instrument rated, and both had previous experience flying long range navigation equipment. Table 2.2 presents a breakdown of the flight hours and qualifications for each pilot.

Table 2.2 Project Pilot Experience

PILOT	TOTAL TIME	COMM.	INST.	ATR	PREVIOUS LONG RANGE NAV. EXP.
A	35,000 hrs	X	X	X	Omega/Loran-C
B	35,000 hrs	X	X	X	Omega/Loran-C

All enroute segments were flown by the primary subject pilot. The copilot acted as safety observer and was also responsible for ATC communications and data entry into the Omega/VLF system. The flight observer was tasked with operation of the data acquisition system and the manual logging of unusual flight situations, such as deviation due to weather or ATC requests.

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3.0 VEHICLE AND EQUIPMENT

3.1 AIRCRAFT

The aircraft chosen for these flights was a Beechcraft Queen Air 65. This vehicle was chosen for its economy, large cabin space and gross weight payload capability. Data acquisition equipment was well within maximum gross weight limits with a full load of fuel, full crew and required support personnel. Aircraft range in the data collection configuration was approximately 6 hours plus reserve. All flight legs were planned to be approximately 4.5 hours in length leaving an adequate margin for unexpected flight conditions.

The Queen Air was leased by Systems Control Technology, Inc. and dedicated to this program during the data collecton segment of the flight schedule. The subject pilots were familiar with the operation of this aircraft, reducing the need for additional pilot familiarization flights. The aircraft was equipped with an EDO Century III autopilot system, a Collins FD-105 flight director system, dual communication radios, dual VOR navigation radios, KNC-610 RNAV system and an altitude encoding transponder. VOR/DME navigation system outputs were displayed on the FD-105 flight director system consisting of a horizontal situation indicator (HSI) and attitude direction indictor (ADI) with a command steering display. During the data collection activity, a dedicated course deviation indicator (CDI) display was utilized to display Omega/VLF steering commands at all times. The safety observer monitored aircraft position by conventional VOR navigation using a standard CDI display on the right side of the front instrument panel. The ARINC 599 Omega/VLF display unit was mounted in the center console between the two pilots.

The aircraft was equipped with static wicks manufactured by TCO Manufacturing, Inc. Three wicks were installed on each control surface which provided more than the adequate number of static discharge points.

3.2 ARINC 599 OMEGA/VLF NAVIGATION SYSTEM

The ARINC 599 receiver used for the project was a fully automatic, aircraft navigation system utilizing the three very low frequency (10.2, 11.33,13.6 kHz) signals transmitted from the network of eight Omega ground stations, and phase stable signals from a network of VLF communication stations. The system consists of three units: an antenna coupler unit (ACU), receiver-processor unit (RPU) and control display unit (CDU).

The ACU takes the form of an orthogonal loop H-field antenna, E-field antenna, or other special purpose antennas, all with bulit-in preamplifiers. For the purposes of this project an E-field antenna was utilized. After carefully skin mapping the aircraft, it was determined that the skin currents precluded the use of an H-field antenna. A flat plate E-field antenna was installed close to the empennage on the underside of the fuselage.

The RPU embodies the receiver and the processor components of the system. The receiver is a three channel device which together with associated circuitry provides excellent signal acquisition. The processor

memory is comprised of read only memory (ROM), random access memory (RAM), and erasable, programmable, read only memory (EPROM) components. The primary navigation programs are contained in the EPROM section. The system will retain the last computed and displayed navigation data during extended power interruptions. The computation of signal phase correction data, selection of stations and navigation mode selection is fully automatic.

The CDU provides comprehensive displays of navigation and steering data as depicted in Figure 3.1.

3.3 MULTIPLE DME POSITIONING SYSTEM

The multiple DME system used in the project was a Rockwell-Collins DME-700. The DME-700 transmitted pulsed signals to a ground station and received responses from the station. Range was determined by measuring the signal propagation time from the aircraft to the station and back to the aircraft. The DME-700 was capable of operating in several modes including: standby, single channel, diversity, and scan (which was utilized for the purpose of this test). The scan mode provided a capability to service up to five stations at a high rate, and scan the other 274 available DME channels for valid replies at the same time. The DME-700 obtains serial digital control information on one of two ARINC 429 input data buses. The control information also instructed the DME as to what mode of operation to use. The DME-700 delivered serial digital distance data over two ARINC 429 output data buses. DME data (distance and frequency) from the five closest DME stations were delivered via the data output buses at a one second rate. Depending on the number of stations received, data from an additional 15 (fifteen) DME stations were also delivered via the data output buses.

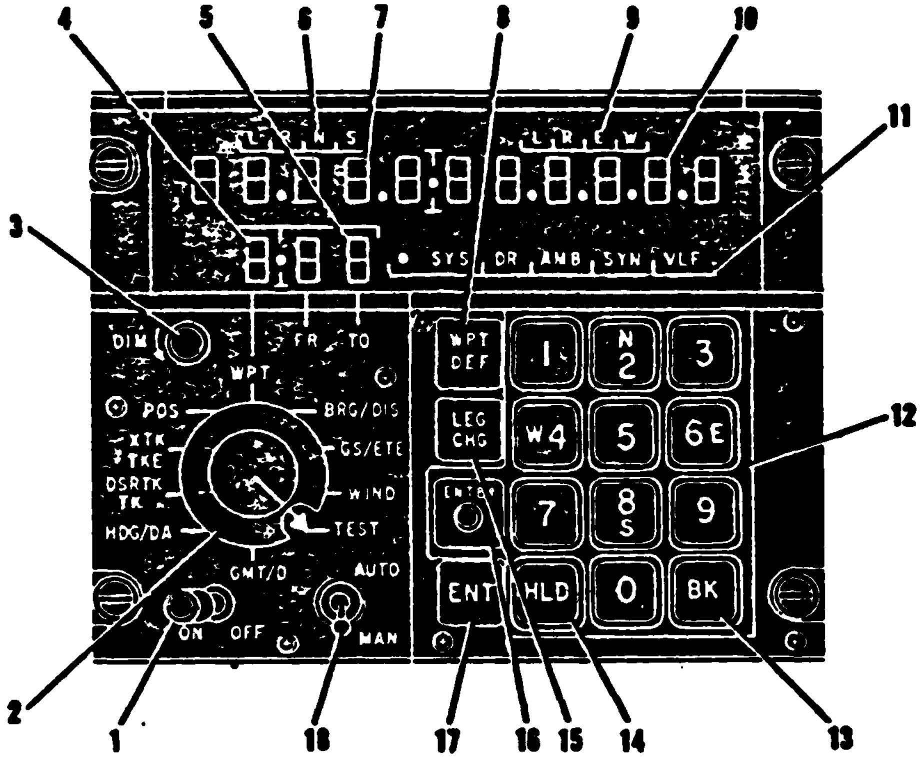
3.4 DATA ACQUISITION AND RECORDING SYSTEM

The data acquisition package utilized during the flight program consisted of seven major components. They were as follows:

- MFE 452B w/424 PAR Cassette Recorder
- Collins DME-700
- VOR Digital Converter
- Dynamic Pressure TAS System
- Microcomputer Chassis, Logic and Interface Boards
- Keyboard and Alphanumeric Display
- Omega/VLF Receiver Processor Unit (RPU)

The appropriate data parameters were digitally recorded on the MFE 452B cassette recorder. These data were recorded from three distinct sources via the microcomputer logic and interface boards. The three

CONTROL DISPLAY UNIT



1. ON/OFF switch; sets the ARINC 599 Omega Navigation System ON or OFF.
2. DISPLAY MODE SELECTOR SWITCH-Selects data for presentation on the left and right numerical displays.
3. DIMMER CONTROL (DIM)-Allows intensity or illumination of displays to be adjusted as required.
4. WAYPOINT NUMBER DISPLAY (WPT)-Shows which waypoint coordinates are being displayed on the left and right displays.
5. FROM/TO WAYPOINT DISPLAY (FR TO)-Displays FROM waypoint number and TO waypoint number of leg being navigated.
6. ANNUNCIATORS (L, R, N, S)-Displays Left or Right, North or South or are blanked dependent upon the position of the Display Mode Selector Switch.
7. LEFT DISPLAY-Displays the data selected by the Display Mode Selector Switch.
8. WAYPOINT DEFINE KEY (WPT DEF)-Allows entry of waypoint coordinates.
9. ANNUNICIATORS (L, R, E, W)-Displays Left or Right, East or West, or are blanked dependent upon the position of the Display Mode Selector Switch.
10. RIGHT DISPLAY-Displays the data selected by the Display mode Selector Switch
11. ANNUNCIATORS (SYS, DR, AMB, SYN)-Displays system failure (SYS), Dead Reckoning Mode of Operation (DR), Position Ambiguity (AMB), Omega Synchronization status (SYN).
12. DATA KEYBOARD-Provides 12 keys, of which 10 (0 through 9) are used for the insertion of data e.g., present position, waypoints, GMT/D and From To waypoint numbers, etc.
13. BK KEY-Allows data entry to be back-spaced one digit at a time if an error is made during the entry. Also frees information frozen by HOLD POSITION operation
14. HOLD POSITION KEY (HLD)-Allows present position information to be frozen.
15. LEG CHANGE KEY (LEG CHG)-Allows manual initialization of leg change.
16. ENTER INDICATOR-Indicates Omega Land Navigation System is in the Data Entry Mode.
17. ENTER KEY (ENT)-Transfers entered data into the Receiver Processor Unit.
18. AUTOMATIC/MANUAL LEG CHANGE SWITCH (AUTO/MAN)-Allows for automatic sequential selection of route legs, or manual selection of route legs.

Figure 3.1 Omega/VLF Control Display Unit

sources were as follows: Collins DME-700, analog voltages representing aircraft systems and the ARINC 599 receiver. The operator/system interface components consisted of a keyboard, alphanumeric display and a CRT console, to be used for post-flight quick-look data dumps. The primary power for the data acquisition system was 28 VDC.

In addition, a second recorder supplied by the Omega/VLF receiver manufacturer was utilized to record signal strength data. Signal numbers, related to signal-to-noise ratio, were recorded for all eight Omega stations at frequencies of 10.2 and 13.6 kHz. Also, signal numbers were recorded for seven VLF stations utilized by the system. The stations utilized by the system are listed in Table 3.1. These data were recorded at 30 second intervals on magnetic cassette tape.

Table 3.1 ARINC 599 Receiver Omega/VLF Stations

Omega Stations	VLF Stations
A Norway	NWC Australia
B Liberia	NDT Japan
C Hawaii	GBR England
D North Dakota	NAA Maine
E Reunion	NPM Hawaii
F Argentina	NSS Maryland
G Australia	NLK Washington State
H Japan	

3.5 SYSTEM CHECKOUT AND CALIBRATION

The Omega/VLF navigation system and the airborne data acquisition system were checked out in a series of calibration flights in the West Palm Beach area prior to beginning flights for data collection. At the same time, the crew utilized the navigation equipment and became proficient in its operation. The training series consisted of local enroute flights and approaches.

Operational validation and calibration of the ground truth and data acquisition system were accomplished in the West Palm Beach area. The calibration flights consisted of two enroute phases (approximately two hours). Automatic DME selection functions were checked as well as the accuracy of the multilateration ground truth system.

Total flight time required for familiarization/calibration was approximately four hours. Operationally, the calibration was conducted using the procedures and guidelines laid down for the overall flight.

4.0 DATA PROCESSING AND PROCEDURES

The data obtained during the flights consisted of digital data recordings on magnetic tape and observations of the pilots and flight observer. The digital data recording system recorded three generic types of navigation and aircraft system data. These types were:

- Analog voltage or phase angle data
- DME digital data
- Omega/VLF digital data

All data were time tagged by the data collector clock to the nearest .01 second. Data were recorded at a 1Hz rate on magnetic tape cassettes. During the entire flight, data were recorded continuously. In all, 70 cassettes of data were obtained. Due to the large amount of data, processing was performed at a 0.1 Hz rate, thereby, providing data at ten second intervals.

All flight data were processed with the contractor's microcomputer system. The system consists of a North Star Horizon microcomputer system controlled by a Zilog Z-80 microprocessor. The system has four 5.25 inch floppy disk drives, a line printer, a digitizer tablet, and a small, flatbed incremental plotter.

All digital data were transmitted from the airborne data recorder to the North Star computer and stored on floppy disks. Data processing programs were written in North Star Basic or Z-80 Assembler.

Presently, Advisory Circular AC 90-45A is the area navigation accuracy standard established by the FAA. The data presented in this report (i.e. alongtrack and crosstrack accuracy data) are presented in a form compatible with AC 90-45A.

4.1 CHARACTERISTICS OF THE DATA

The following analog data were recorded during the project and utilized in the data reduction procedure:

- dynamic pressure (indicated airspeed)
- altitude reference } potentiometer voltages
- altitude wiper } potentiometer voltages
- aircraft heading synchro
- CDI indicator voltage
- CDI flag voltage

Each of the analog channels was calibrated in the contractor's laboratory and on the ground with the equipment installed in the aircraft.

Seven DME data channels from the Rockwell-Collins DME-700 were obtained each second. Each channel contained a time tag, co-channel VOR frequency and DME distance. In areas where there were five or more DME stations available, the DME-700 provided DME measurements from five separate stations. The additional two channels contained data from two of the five channels taken about a half second later. When fewer than five stations were available, the DME-700 provided repeated measurements from the available stations to complete the seven channels of data.

The Omega/VLF information is divided into two general categories; Omega/VLF signal processing data and Omega/VLF navigation data. Specific parameters recorded in these categories were:

<u>Omega/VLF signal processing data</u>

- Omega/VLF signal numbers (0 to 100)
- Stations used in the position solution

<u>Omega/VLF Navigation data</u>

- Omega/VLF latitude and longitude
- Distance to waypoint
- Desired track
- Greenwich Mean Time (GMT)

Omega/VLF navigation data were recorded at a 1 Hz rate and were time tagged to the nearest .01 seconds. Omega/VLF signal data were recorded at a 1/30 Hz rate.

4.2 GROUND TRUTH DATA PROCESSING

The ground truth data processing consisted of converting the DME measurements from the DME-700 into aircraft position.

4.2.1 DME Processing

The processing of the DME information to determine aircraft position was the most time consuming aspect of the data processing. The major elements of the procedure are shown in the block diagram in Figure 4.1.

The procedure began with the operator providing an initial estimate of the aircraft's position. This was generally provided by using the latitude and longitude coordinates of the nearest VOR facility or an airport reference point. Next, the DME information was read from the floppy disk containing the test data. The DME frequency (or more

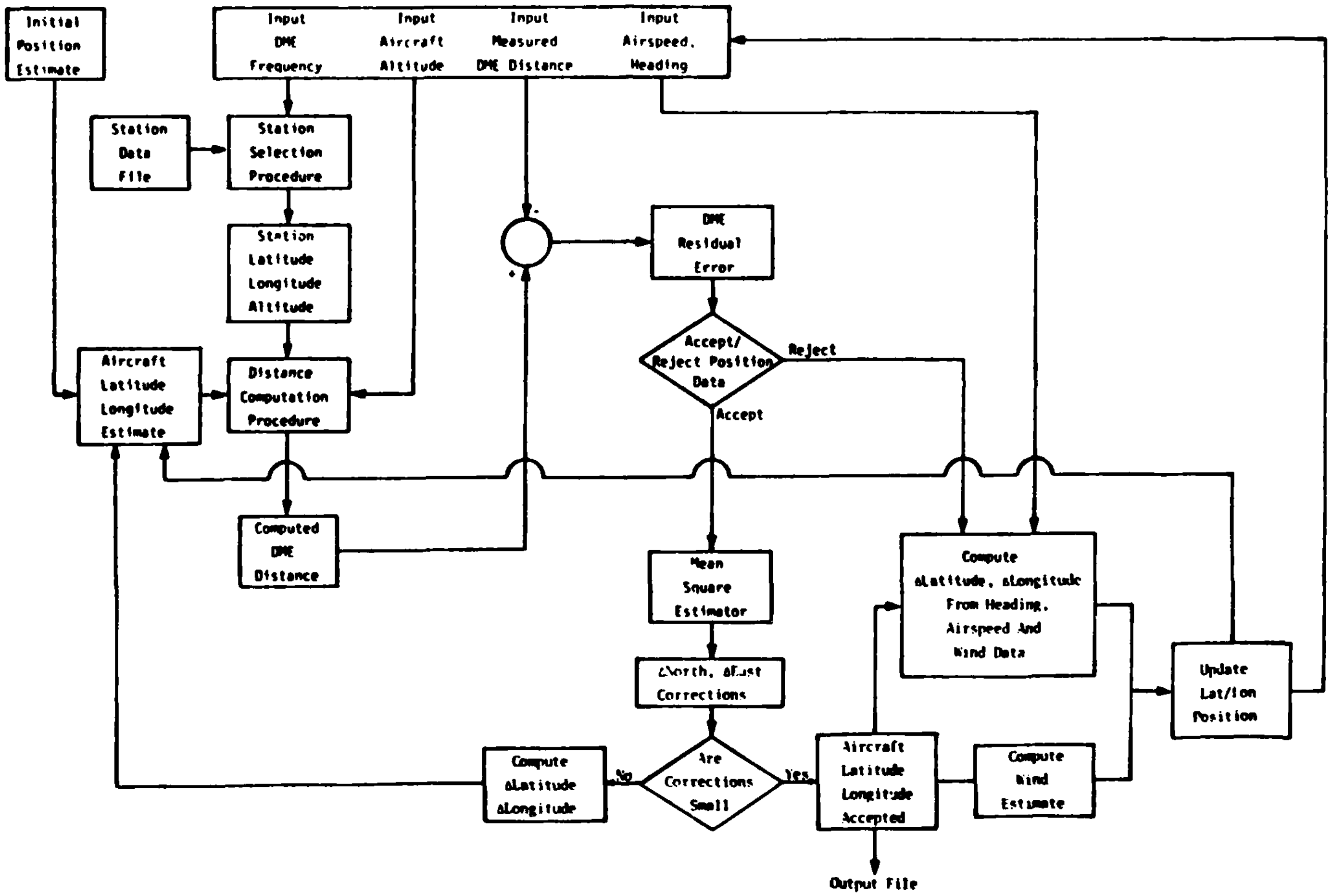


Figure 4.1 DME Positioning System Block Diagram

correctly, the VOR co-channel frequency) was used to identify the station being received. A data file of DME stations, their coordinates, altitude, magnetic variation and their co-channel VOR frequency was maintained for this purpose.

The aircraft position estimate and the DME station coordinates were used to compute a corresponding DME distance. An earth model with the Sodano formula for earth oblateness was utilized for this purpose (Reference 1).

The recorded DME distance was corrected for the slant range error and compared with the computed DME distance. The difference was called the DME residual error. The residual error was passed to a mean square estimator of northing and easting corrections. Details of the estimation procedure are contained in Appendix A.

If the easting and northing corrections to the position estimate were sufficiently small, the aircraft position estimate was conditionally accepted as the aircraft's true position. The criteria used for acceptance was:

$$|\Delta\mathrm{East}| + |\Delta\mathrm{North}| < .01\mathrm{NM}$$

where ΔE is easting correction
ΔN is northing correction

The condition on the acceptance of the point was that the root mean square value of the sum of the residuals be less than some threshold value. For these tests the threshold was set at 0.08 NM, which was 5% of the enroute alongtrack error criteria set forth in Advisory Circular 90-45A. When Omega/VLF was measured against position fixes from the DME system which met this criteria, the DME position error contributed negligible error with reference to AC 90-45A criteria.

If the aircraft position was accepted, the data were placed in an output file for future use in the analysis of Omega/VLF accuracy. Furthermore, the coordinates were used to compute an estimate of wind. The aircraft's next position estimate for the next record time (usually 10 seconds later) was made from heading, airspeed and wind values by dead reckoning procedures. If the point was rejected for any reason, the original aircraft position estimate was updated by dead reckoning to the next record time and the procedure was repeated.

In addition to the residual criteria, the DME data had to pass four additional tests. These were:

- a sufficient number of DME stations
- a theoretical position fix accuracy (DRMS value) which exceeded a 0.3 NM threshold

- the correction procedure had to converge in 20 or less iterations

- the denominator of the least square estimator had to be non-zero

An expression for the theoretical position fixing accuracy (or DRMS) of the DME system is contained in Appendix A.

4.2.2 Analog VOR/DME Processing

In the event that a sufficient number of DMEs were not obtained at any time, an estimate of the true position of the aircraft was obtained from analog VOR and DME data. VOR bearing was measured to one degree and DME distance was measured to 0.1 NM. Bearing and distance equations and the location of the reference station were used to calculate an estimate of the aircraft's true position.

As with the previous DME processing, upon acceptance of this position, the data were placed in an output file for future use in the analysis of Omega/VLF accuracy.

The aircraft DME, which was used in this procedure, became inoperative during the test and scanning DME measurements from the DME-700 were substituted when they were available from the VOR reference station.

4.3 OMEGA/VLF ACCURACY

Through the use of the aircraft's true position, and the navigation and Omega/VLF data recorded from the Omega/VLF navigator, many accuracy parameters could be determined. These include:

- easting and northing position errors
- total system alongtrack and crosstrack errors
- navigation sensor alongtrack and crosstrack errors
- navigation computer alongtrack and crosstrack errors
- flight technical error

A diagram defining these error relationships is shown in Figure 4.2. The navigator RPU data stream provided Omega/VLF derived latitude and longitude, crosstrack deviation (flight technical error -- FTE) and distance to waypoint (DTW) data. From these parameters, and the waypoints which define the course, the other error components were calculated.

Given: LAT_D, LON_D — latitude/longitude derived from the DME data

LAT_O, LON_O — latitude/longitude derived by the navigator

FTE - Omega/VLF flight technical error — recorded data

DTW - Omega/VLF distance to waypoint — recorded data

LAT_{TO}, LON_{TO}, LAT_{FR}, LON_{FR} — coordinates of the "to" and "from" waypoints

Find: ΔN, ΔE — Omega/VLF navigation northing error, easting error

TSCT - Total system crosstrack error (aircraft position relative to intended course)

ATD - Alongtrack distance

NSAT, NSCT — Omega/VLF navigation sensor error in alongtrack and crosstrack coordinates

Step 1: Find northing and easting errors

$$N = (LAT_O - LAT_D) * 60 \text{ nm/degree}$$

$$E = (LON_O - LON_D) \text{ Cos } (LAT_D) * 60 \text{ nm/degree}$$

Step 2: Define Course Geometry

The angle θ_w is the reciprocal angle of the desired course between the "from" waypoint and the "to" waypoint. This angle is calculated using the great circle bearing equation in Appendix A with the "to" waypoint and "from" waypoint coordinates used as input data.

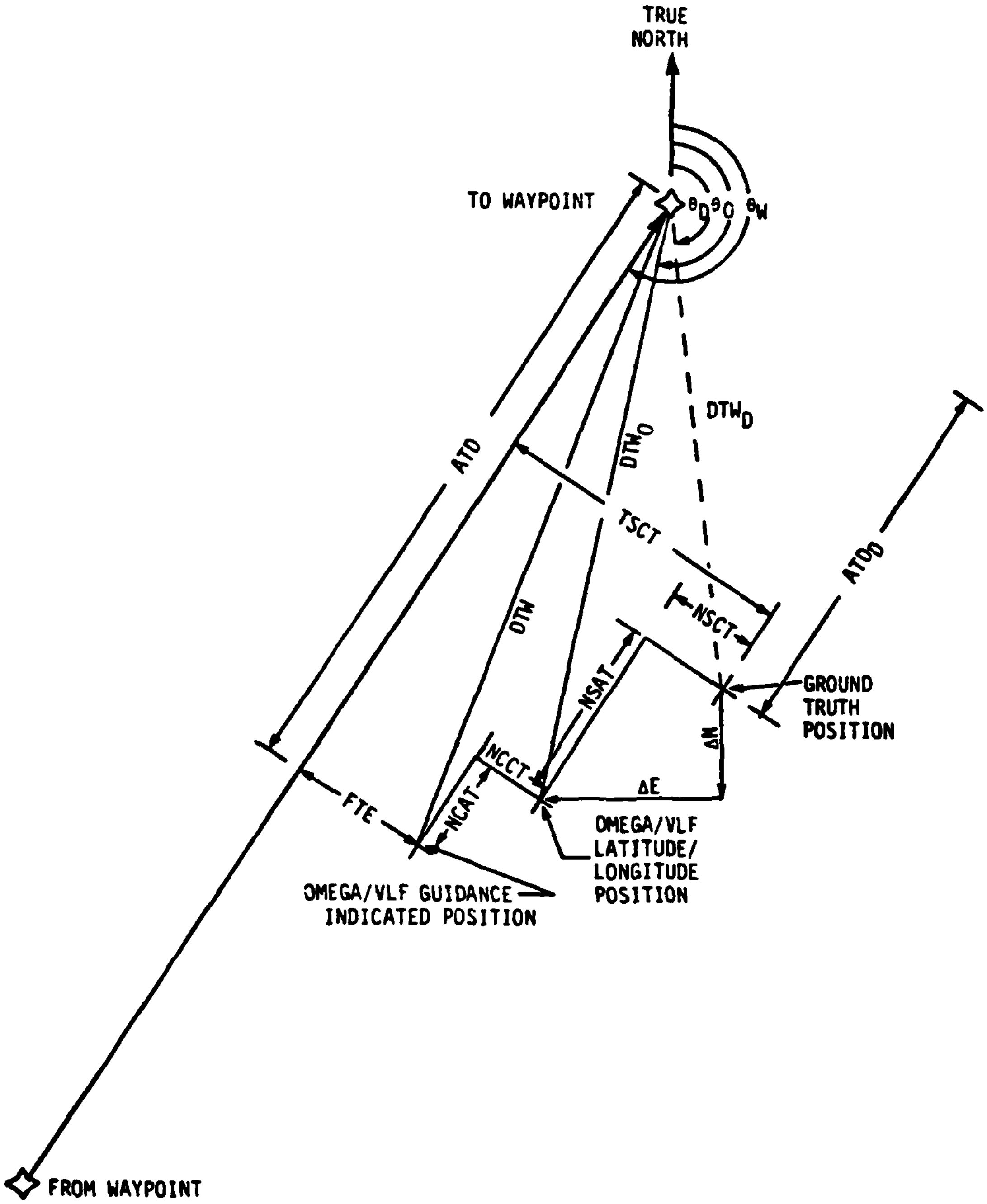


Figure 4.2 Omega/VLF System Error Geometry

Step 3: Find True Aircraft Position

The angle θ_D was the reciprocal angle of the aircraft's bearing to the "to" waypoint as measured from the aircraft's true position. The true distance to the waypoint, DTW_D, and the angle θ_D were calculated using the Sodano distance equation and bearing equations found in Appendix A with the "to" waypoint coordinates used as input data. Then, TSCT and ATD were determined as follows:

$$TSCT = DTW_D * \mathrm{Sin}\ (\theta_W - \theta_D)$$

$$ATD_D = DTW_D * \mathrm{Cos}\ (\theta_W - \theta_D)$$

Step 4: Find track-related Omega/VLF position

FTE and DTW were given

$$ATD = DTW - FTE$$

Step 5: Find navigation computer errors

The values θ_O and DTW_O were computed using the "to" waypoint coordinates and the navigator's latitude, longitude coordinates in the great circle distance and bearing equations in Appendix A. The navigation computer errors were then defined using the following equations:

$$NCAT = ATD - DTW_O * \mathrm{Cos}\ (\theta_W - \theta_O)$$

$$NCCT = DTW_O * \mathrm{Sin}\ (\theta_W - \theta_O) - FTE$$

Step 6: Find navigation sensor errors

The navigation sensor errors were found by subtracting computer error and flight technical error (in the crosstrack case) from the total system error.

4.4 STATISTICAL DATA PROCESSING

The error components were evaluated statistically at points where the Omega/VLF system was used for navigation. Mean values and standard deviations were computed according to standard formulas:

mean value of N samples $x_1, x_2, \ldots x_n$

$$\overline{X} = \frac{1}{N} \sum X_i$$

standard deviation of those samples

$$\sigma_x = \sqrt{\frac{x_i^{\,2} - N\,\overline{X}^{\,2}}{N - 1}}$$

5.0 OPERATIONAL ANALYSIS

In general it was found that the Arinc 599 Omega/VLF receiver tested has been well designed from the pilot's point of view. Most of the features or modes were, at one time or another, used by each of the subject pilots. Most of the time the pilots preferred to keep the digital display readout in the XTE/TKE (crosstrack error and track angle error) mode in order to fine tune their steering performance. Periodically the pilots used the distance to waypoint mode in order to maintain cognizance of their alongtrack position, and used the CDI needle for crosstrack steering. In any event, the Omega/VLF signal stability was good enough that pilot FTE, or steering error, was quite low. Even when flying only with reference to the CDI, needle movement was only affected by aircraft heading or wind, and did not exhibit the significant variations often encountered with either flying VOR radials, or, to a lesser extent, when flying VOR/DME RNAV. It is to be expected that the FTE element in an Omega/VLF RNAV system will be substantially lower than the values currently used for the enroute phase of VOR/DME RNAV system certifications.

Only one operationally significant characteristic was observed during the conduct of these tests. On two separate occasions the Omega/VLF system reverted to the dead reckoning (DR) mode. One such occasion occurred approximately 10 nm from the airport on an approach into Flint, MI. The system went into the DR mode and did not resume Omega/VLF navigation for the remainder of the flight. It should be noted that there was no problem getting the system to synchronize on the ground at Flint before the next flight.

The other time this problem was noticed was near Fargo, ND on a flight from St. Paul, MN to Dickinson, ND. The system reverted to the DR mode and did not resume Omega/VLF navigation for the remainder of the flight. Repeated attempts were made to update the system in the air, but all attempts failed.

One possible explanation for this failure to reacquire navigation might be related to the fact that no TAS (True Airspeed System) was installed in the aircraft. Since the system required approximately 4-5 minutes to "lock-on" and extinguish the DR light and AMB (ambiguity) light, it may reasonably be assumed that the system was not able to adequately determine its position to resume normal Omega/VLF navigation while the aircraft was in motion. Heading and TAS were two essential items required by the system to track in the DR mode. Without TAS it was possible the system could not accurately track its present position in the DR mode so that it could synchronize and acquire the correct position while airborne.

It can be reasonably assumed that many general aviation and helicopter users will have no TAS capability to aid the Omega/VLF system. An inability to reaquire navigation would pose a significant operational deficiency. A possible alternative to mechanical inputs of TAS (and even heading) would be manual inputs of these values through the keyboard of the navigator to aid the system in reaquiring navigation while the aircraft is moving.

During the 51 hours of flight testing no other operational problems were experienced. The system was easy to operate and interfaced well with the present ATC system. The following section will describe in detail accuracy results obtained from the flight test.

6.0 RESULTS

This section contains an analysis of the signal coverage and accuracy data recorded during the CONUS Omega/VLF flights. The analysis is divided into six sections which include:

- signal coverage
- DME positioning system performance
- receiver/positioning system performance
- navigation computer performance
- pilot performance
- overall system performance

6.1 SIGNAL COVERAGE

The Omega and VLF signal data were recorded on a Base Ten cassette recorder and were processed by the receiver manufacturer for signal amplitude and phase characteristics. A preliminary set of signal level data was prepared by the manufacturer and provided for this report. These data were in the form of printouts of signal numbers versus Greenwich Mean Time for two frequencies of Omega, 10.2 kHz and 13.6 kHz, for each of the eight Omega stations, and signal numbers for seven VLF stations. These signal numbers ranged from 0 to 100. For Omega, the numbers are directly related to receiver input signal-to-noise ratio (SNR) for a 100Hz bandwidth through the use of a curve provided by the manufacturer. The following list of signal number and SNRs represent some typical points on the nonlinear relationship.

SIGNAL NUMBER	SNR (db/ $\sqrt{100Hz}$)
10	-20
20	-13
75	0
100	+15

A signal number of 13 (-17.5 db/ $\sqrt{100Hz}$) was considered to be the minimum threshold for acquiring usuable Omega signals.

For VLF, the signal numbers cannot be directly related to SNR due to modulation of the signal. The signal number depends upon the mark-space ratio of the VLF signal as well as SNR. For this reason, VLF signal numbers were lower than Omega signal numbers throughout the tests for comparably located stations. A signal number of 20 was the minimum threshold for usable VLF signals.

The raw data for Omega and VLF signal levels were smoothed for graphical presentation. The data for each segment (SNR for Omega and signal number for VLF) were fitted to a second order polynomial of the form:

$$S = A+B\cdot T+C\cdot T^2$$

where S = signal level (SNR for Omega, signal number for VLF)
T = Greenwich Mean Time
A,B,C = coefficients determined by standard fitting methods [2]

Figure 6.1 through 6.14 are plots which depict Omega/VLF signal levels for the fourteen flight segments. The figures show SNR values for the eight Omega stations at two frequencies, 10.2 kHz and 13.6 kHz, and signal numbers for seven VLF stations. All signal level data were plotted as a function of Greenwich Mean Time. The figures show three letter identifiers of VOR stations at the time that the aircraft was directly over the station. Table 6.1 contains a list of these identifiers and their locations.

Other constraints were imposed upon the Omega and VLF signals by the receiver before they were considered appropriate for position determination purposes. These constraints were based upon considerations of modal interference and signal propagation problems that have been observed in very low frequency signals. These constraints were as follows:

- LaReunion was deselected at all times due to the probability of long path signal contamination
- Liberia was deselected during times when any part of the path was in darkness - sunset at Liberia (1900 GMT) to local sunrise (1200-1500 GMT)
- Stations were deselected when the aircraft was operating within 300 nm of the transmitter - North Dakota (Omega), NSS - Annapolis (VLF) and NLK - Washington State (VLF)

6.1.1 Omega Signal Coverage

With reference to Figures 6.1 through 6.14 the following observations were made with regard to Omega coverage:

STATION	OBSERVATION
A-Norway	Received only along the eastern seacoast.
B-Liberia	Received throughout the country except in the Pacific Northwest and during the night flight (Segment 6). Station was deselected on several occasions during periods when any part of the propagation path was in darkness.
C-Hawaii	Received throughout the flight area.

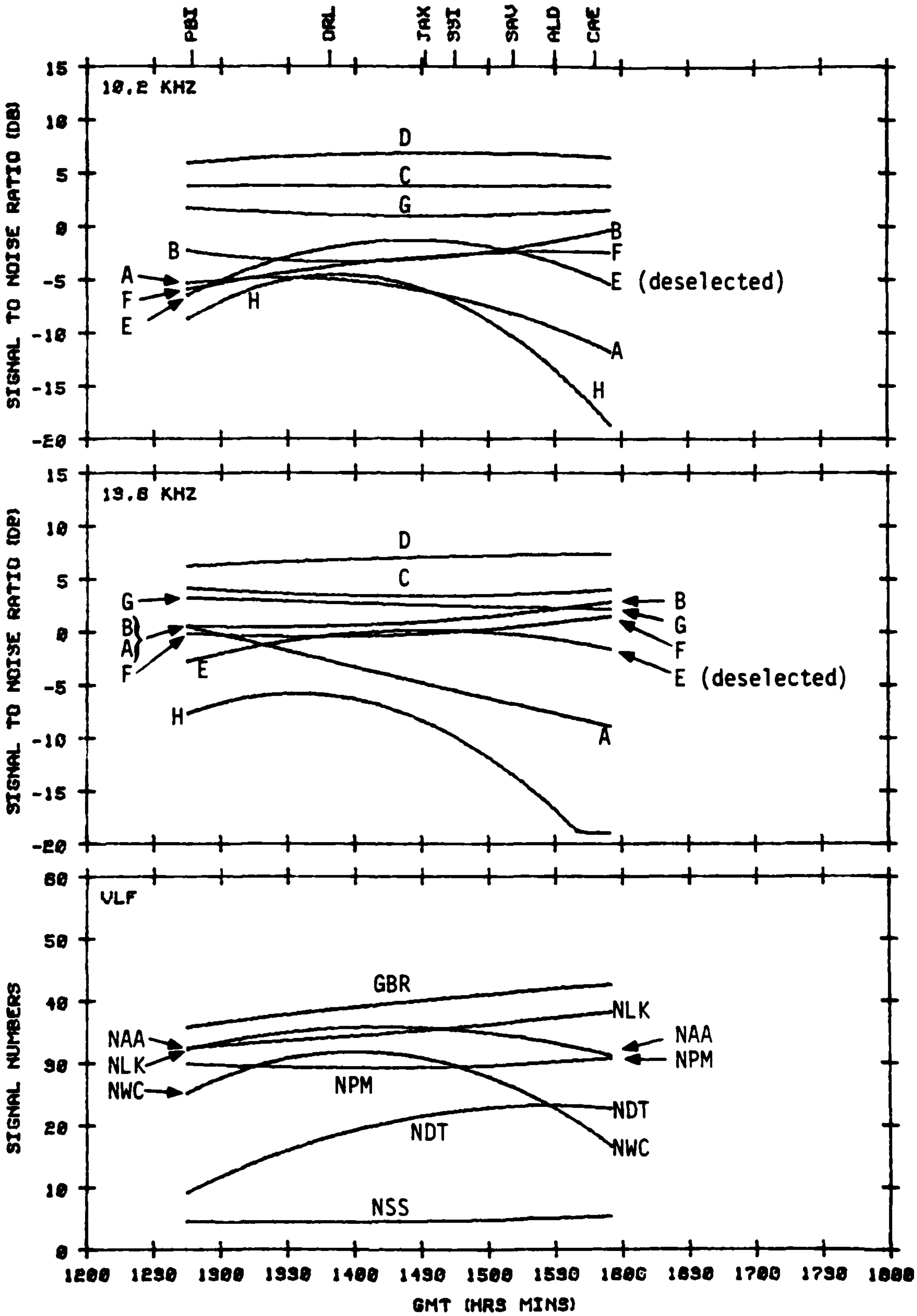


Figure 6.1 CONUS Omega/VLF Signal Coverage for Segment 1, Palm Beach, FL to Columbia, SC (May 9, 1983)

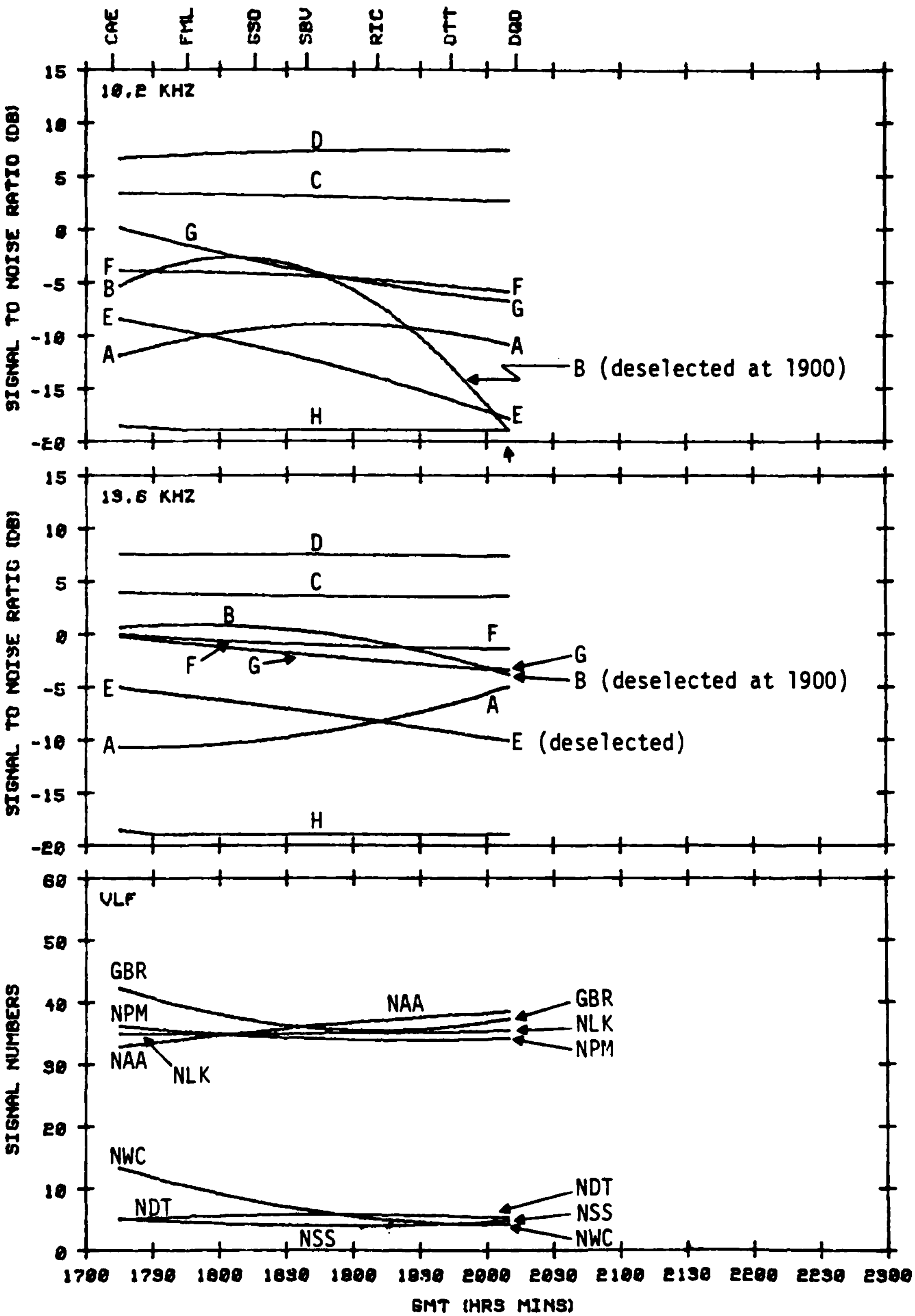


Figure 6.2 CONUS Omega/VLF Signal Coverage for Segment 2, Columbia, SC to Wilmington, DE (May 9, 1983)

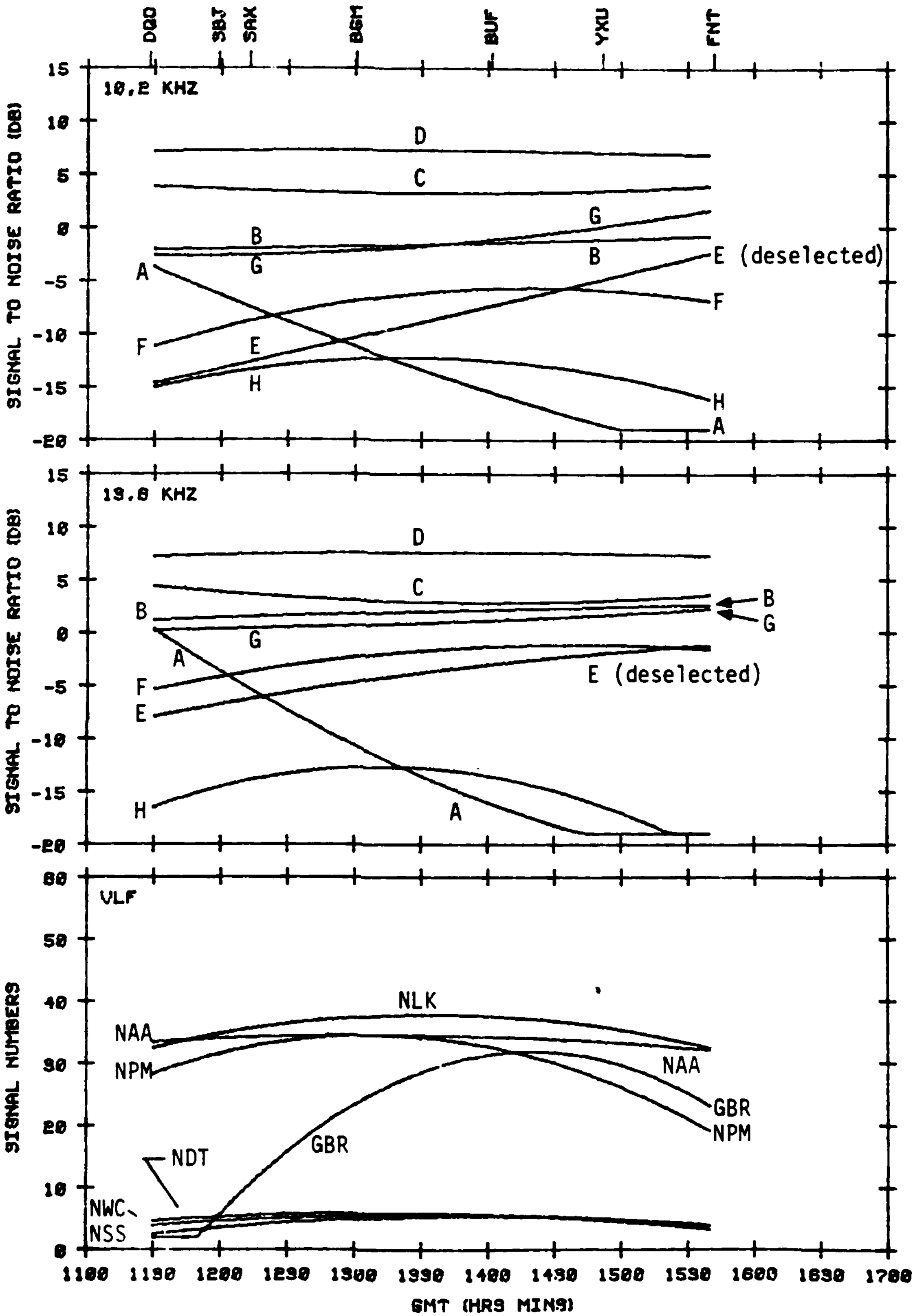


Figure 6.3 CONUS Omega/VLF Signal Coverage for Segment 3, Wilmington, DE to Flint, MI (May 10, 1983)

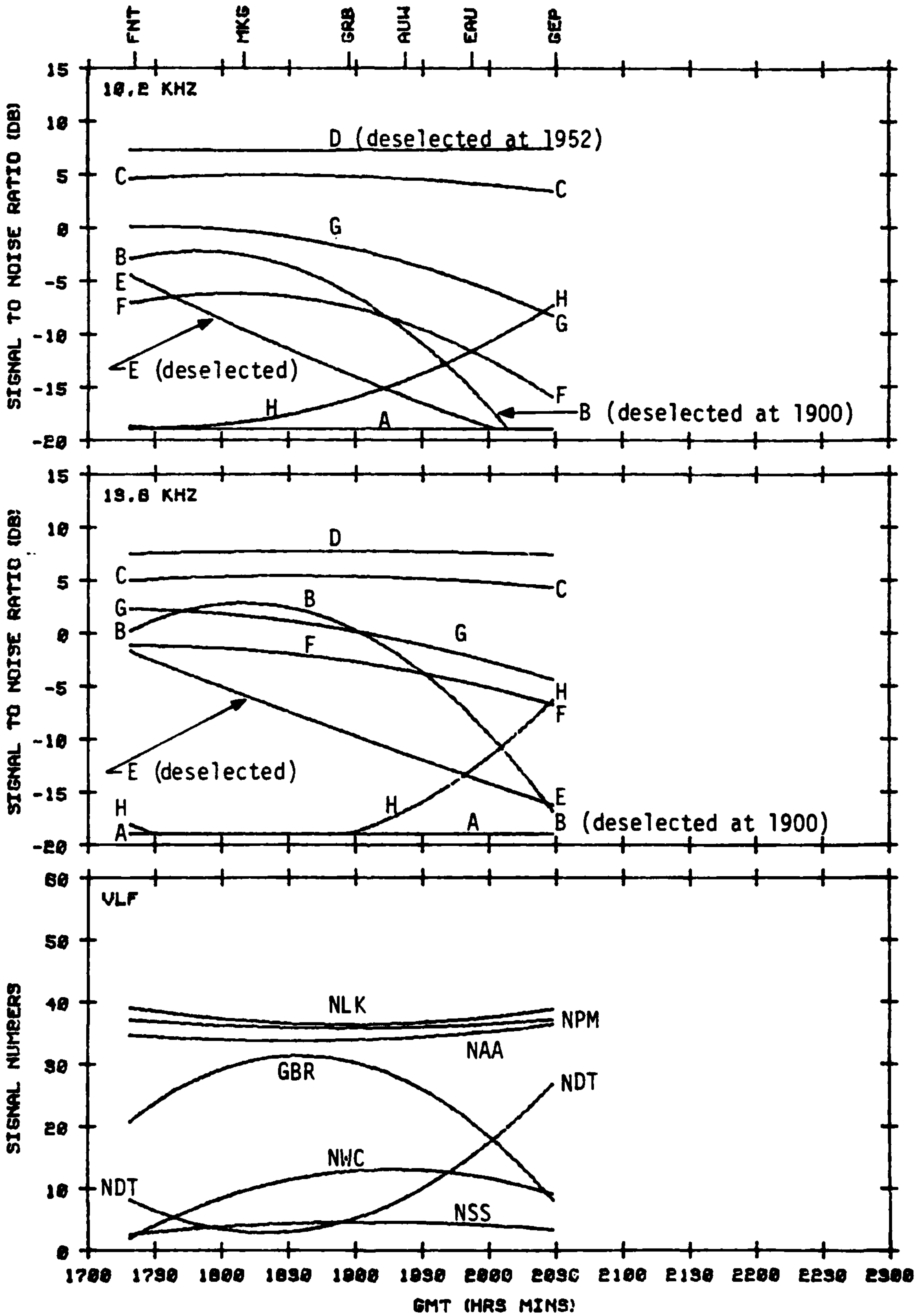


Figure 6.4 CONUS Omega/VLF Signal Coverage for Segment 4, Flint, MI to St. Paul, MN (May 10, 1983)

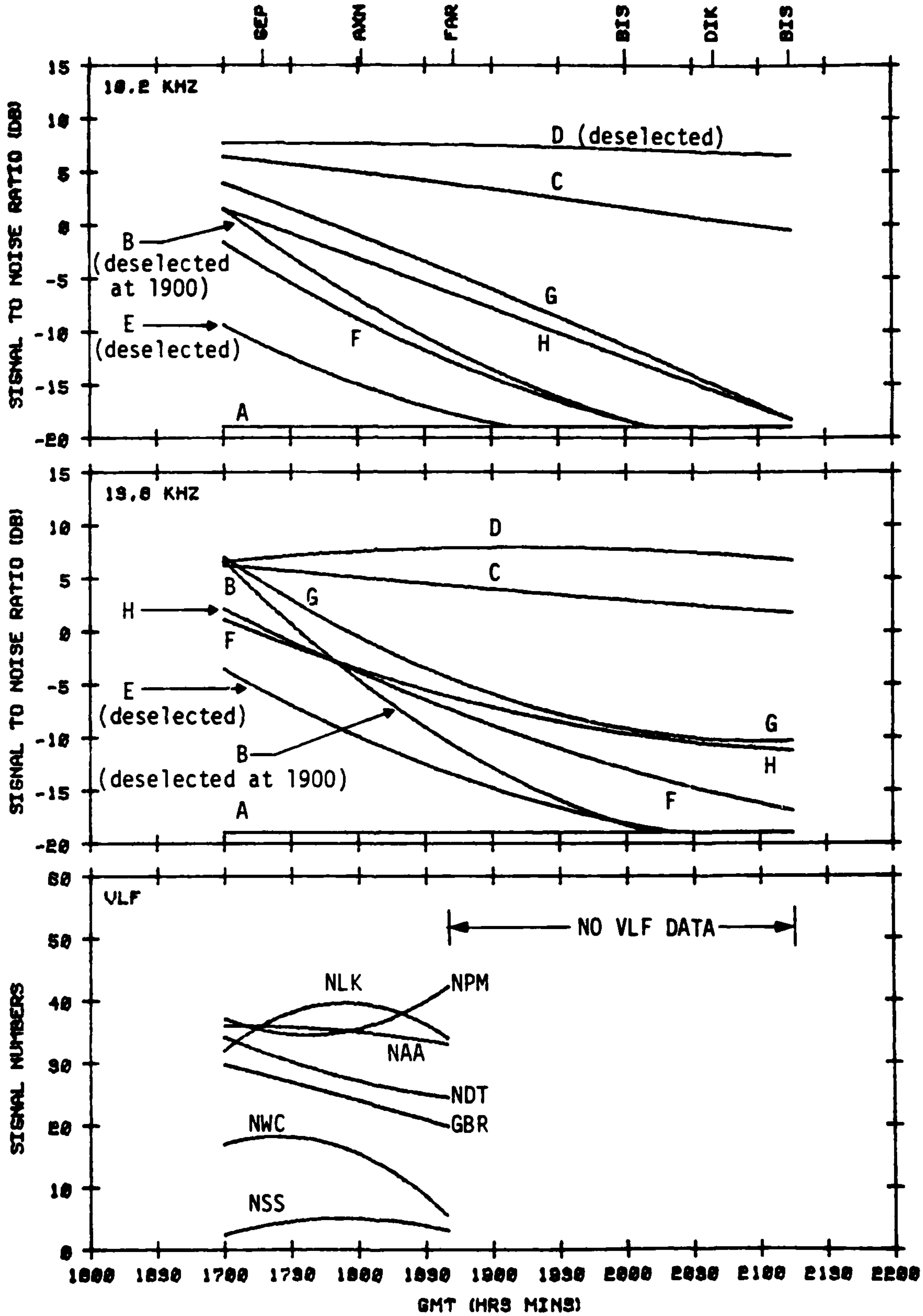


Figure 6.5 CONUS Omega/VLF Signal Coverage for Segment 5, St. Paul, MN to Bismarck, ND (May 13, 1983)

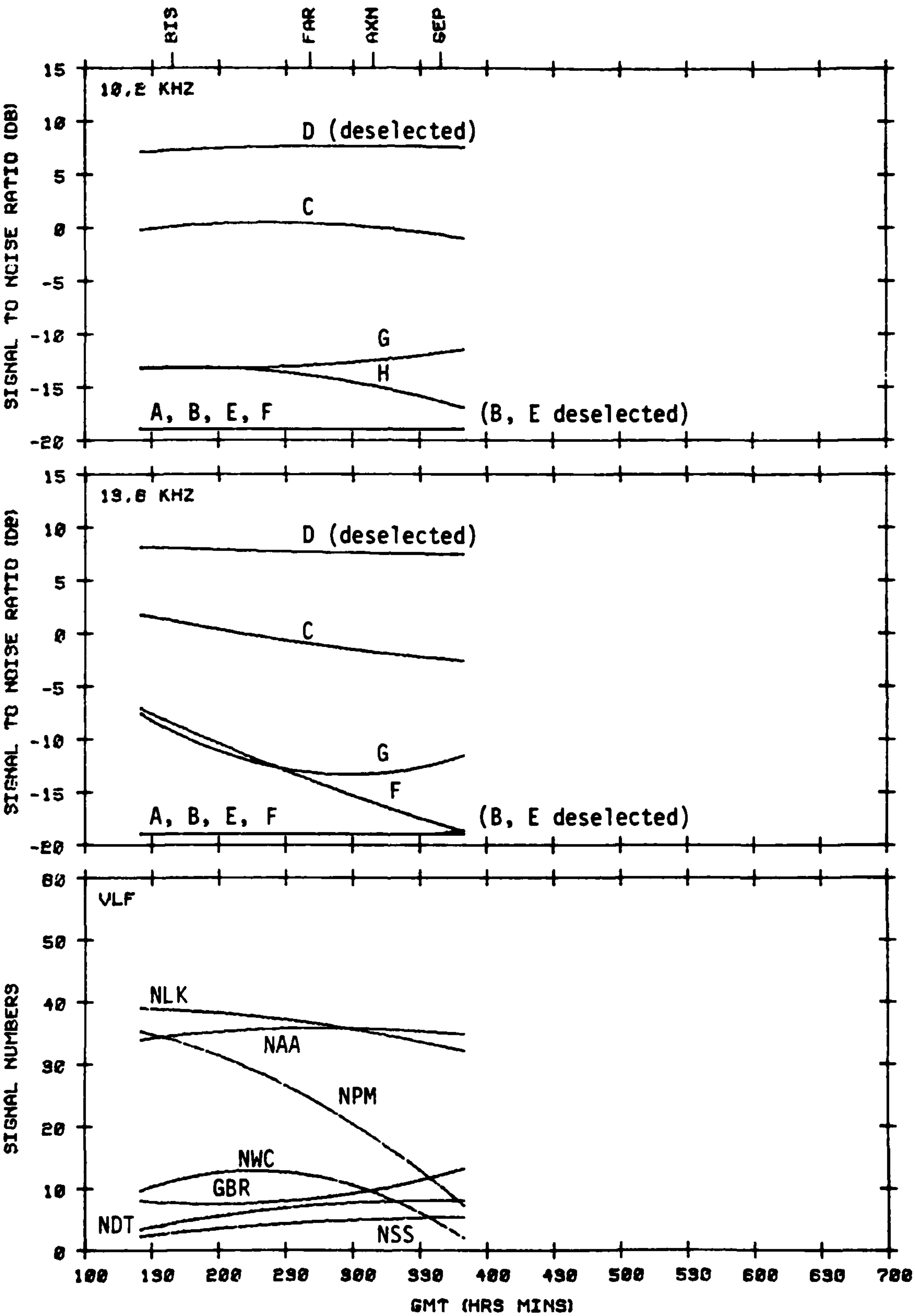


Figure 6.6 CONUS Omega/VLF Signal Coverage for Segment 6, Bismarck, ND to St. Paul, MN (May 14, 1983)

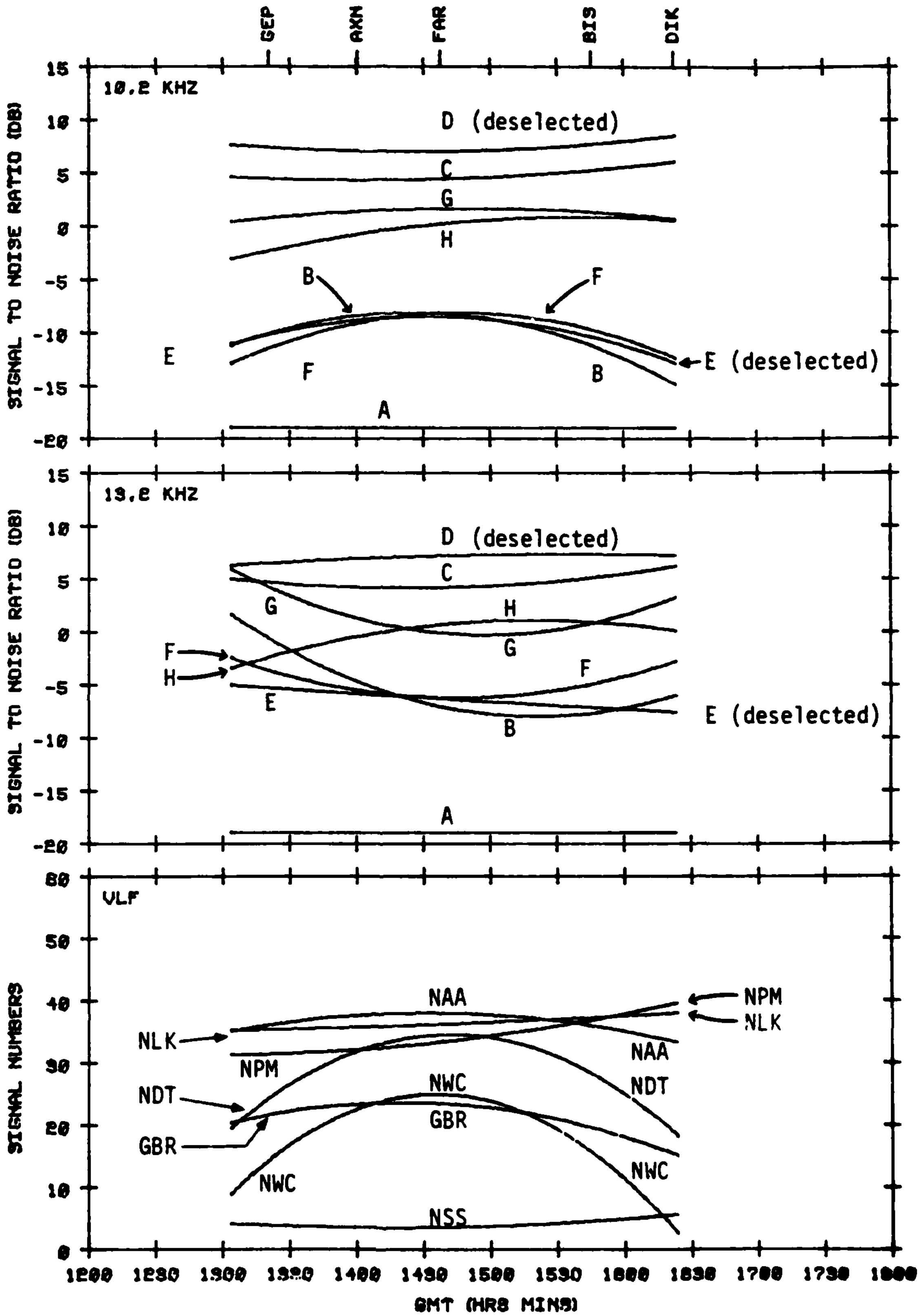


Figure 6.7 CONUS Omega/VLF Signal Coverage for Segment 7, St. Paul, MN to Dickinson, ND (May 14, 1983)

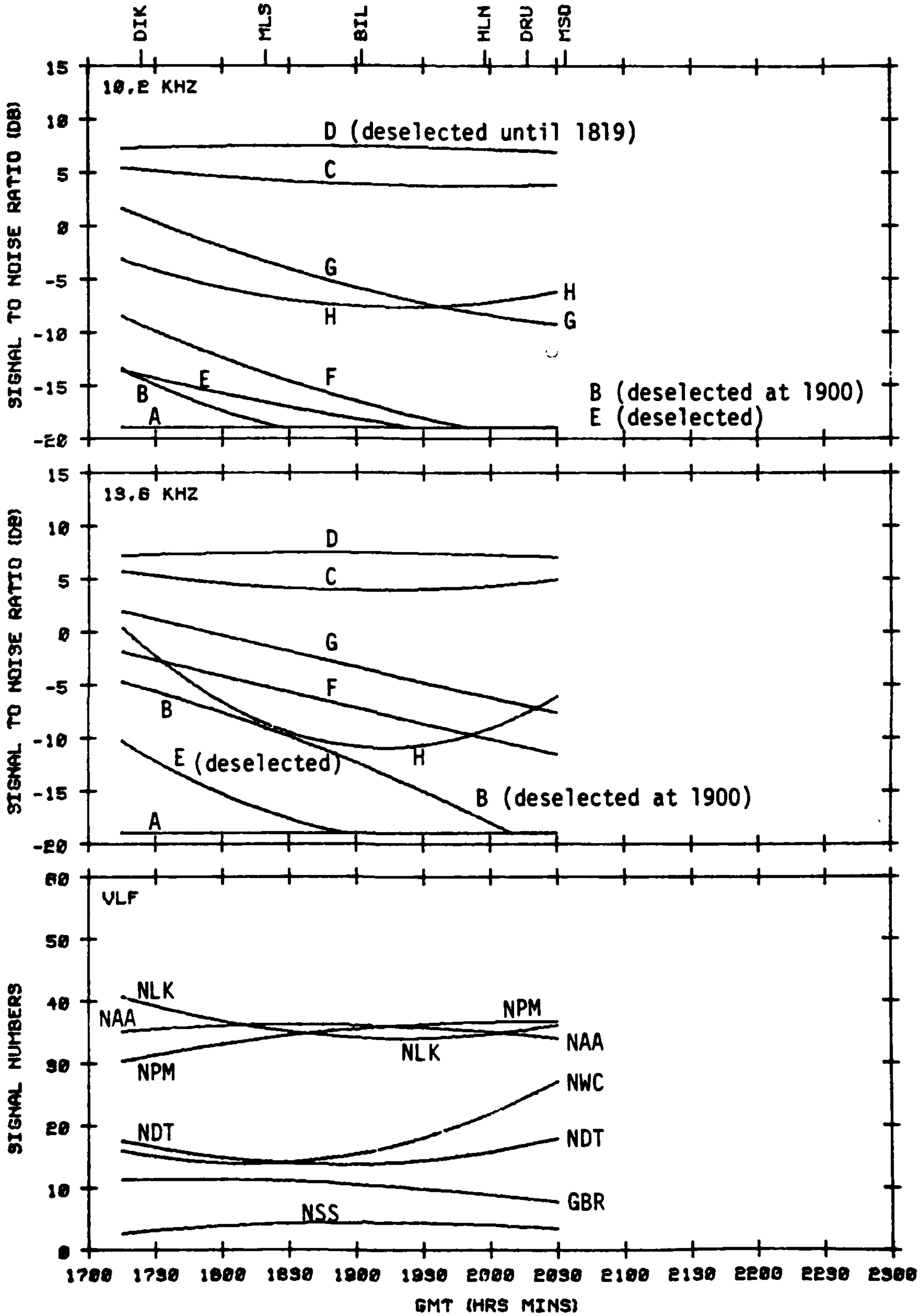


Figure 6.8 CONUS Omega/VLF Signal Coverage for Segment 8, Dickinson, ND to Missoula, MT (May 14, 1983)

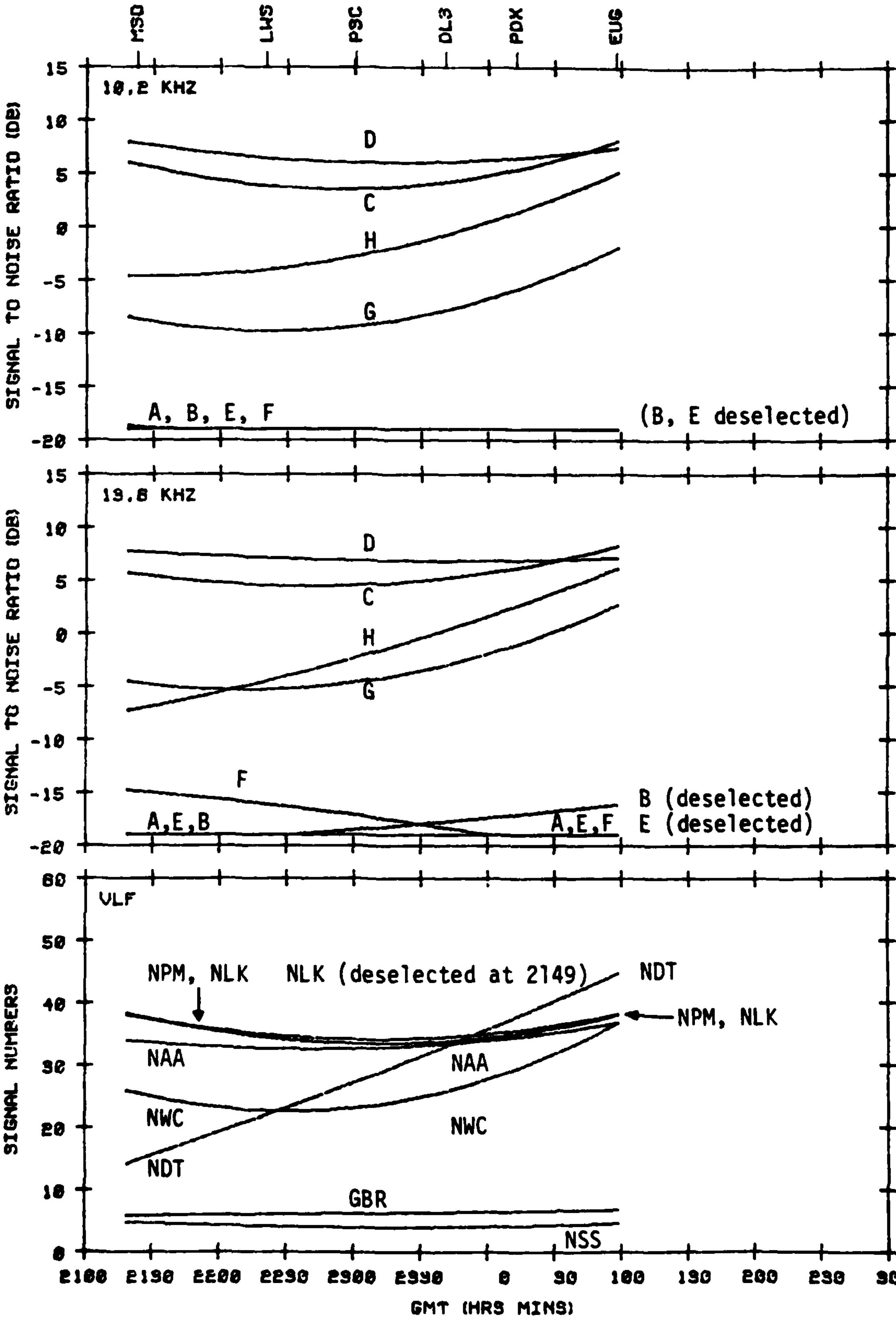


Figure 6.9 CONUS Omega/VLF Signal Coverage for Segment 9, Missoula, MT to Eugene, OR (May 14, 1983)

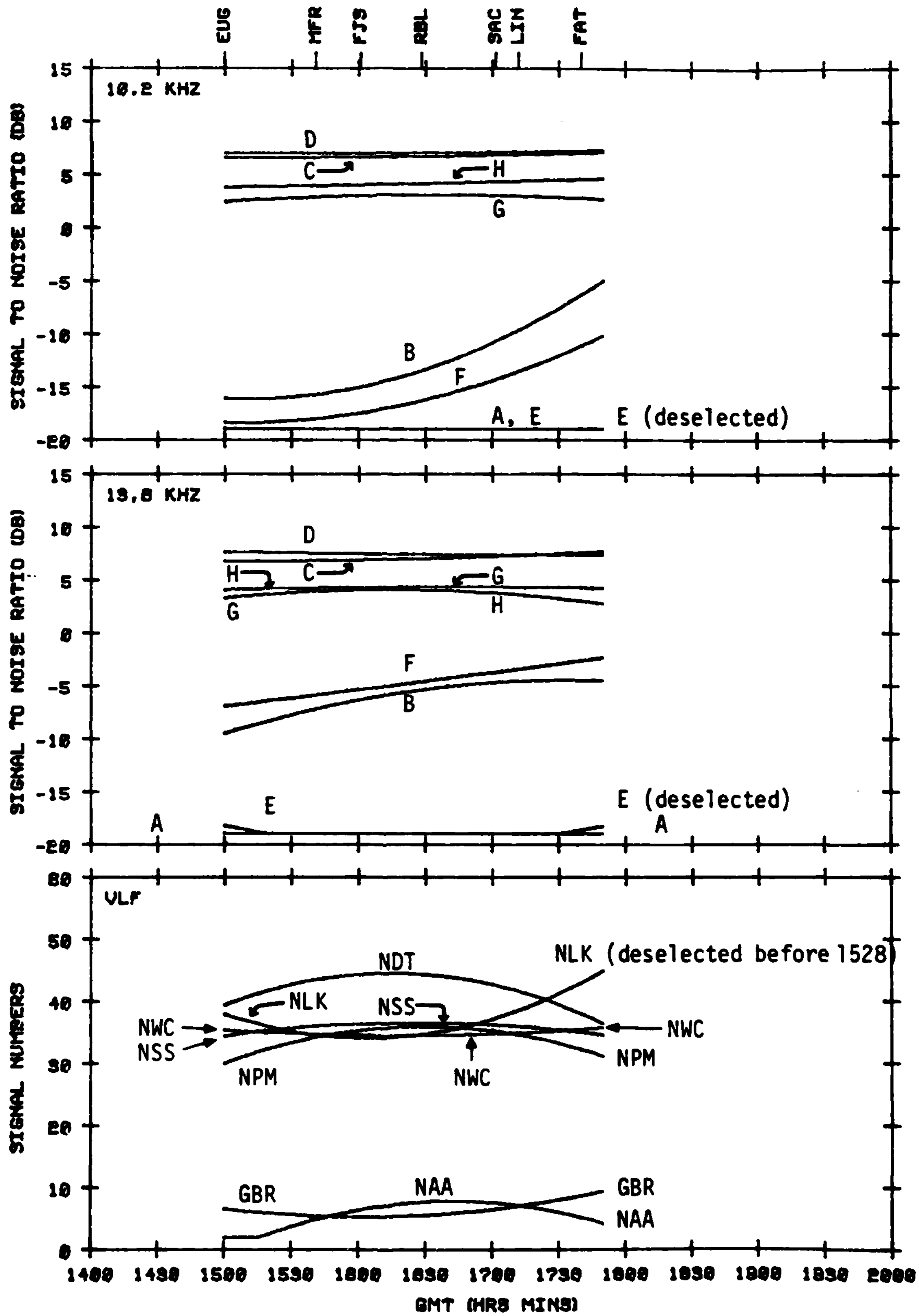


Figure 6.10 CONUS Omega/VLF Signal Coverage for Segment 10, Eugene, OR to Fresno, CA (May 15, 1983)

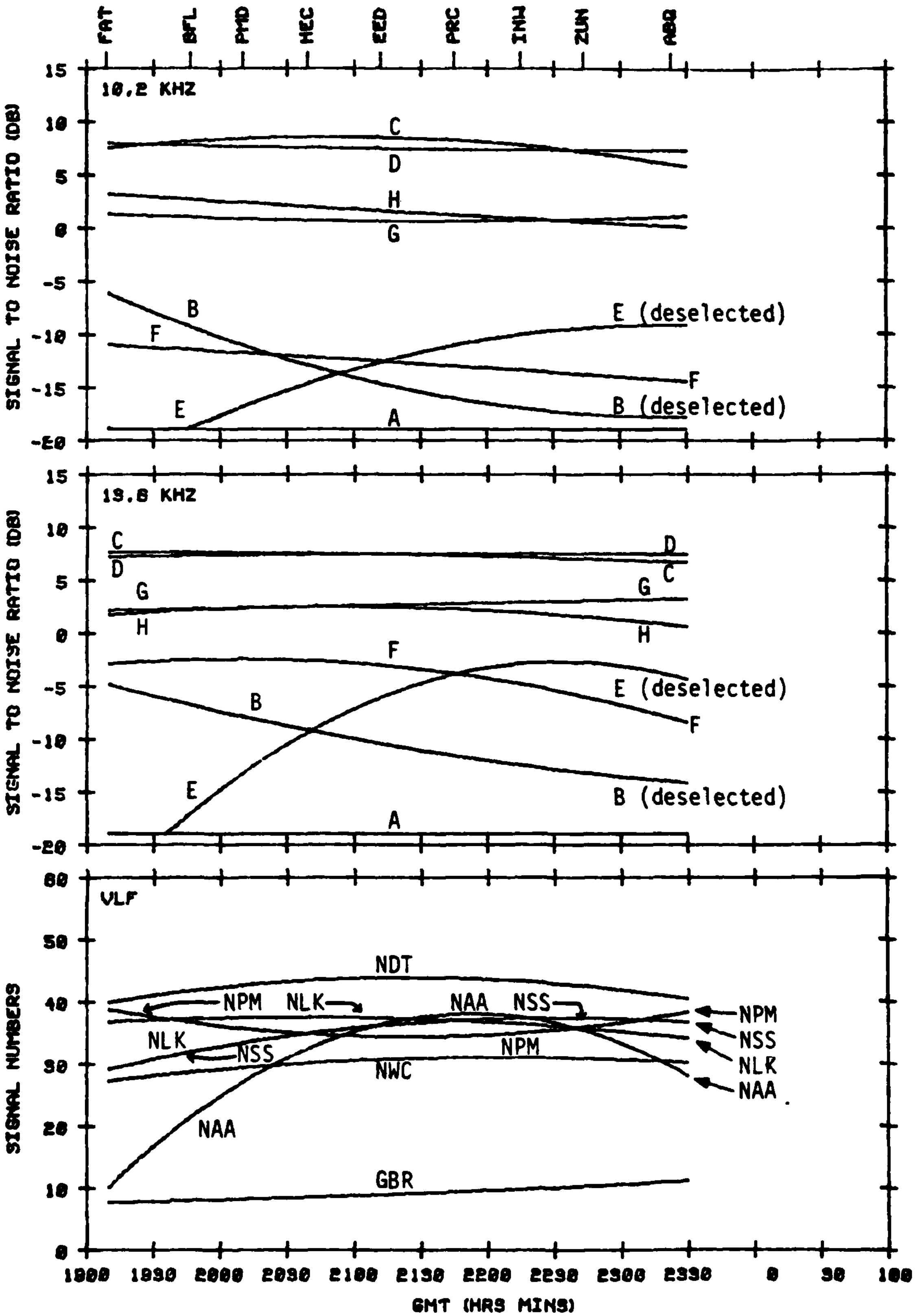


Figure 6.11 CONUS Omega/VLF Signal Coverage for Segment 11, Fresno, CA to Albuquerque, NM (May 15, 1983)

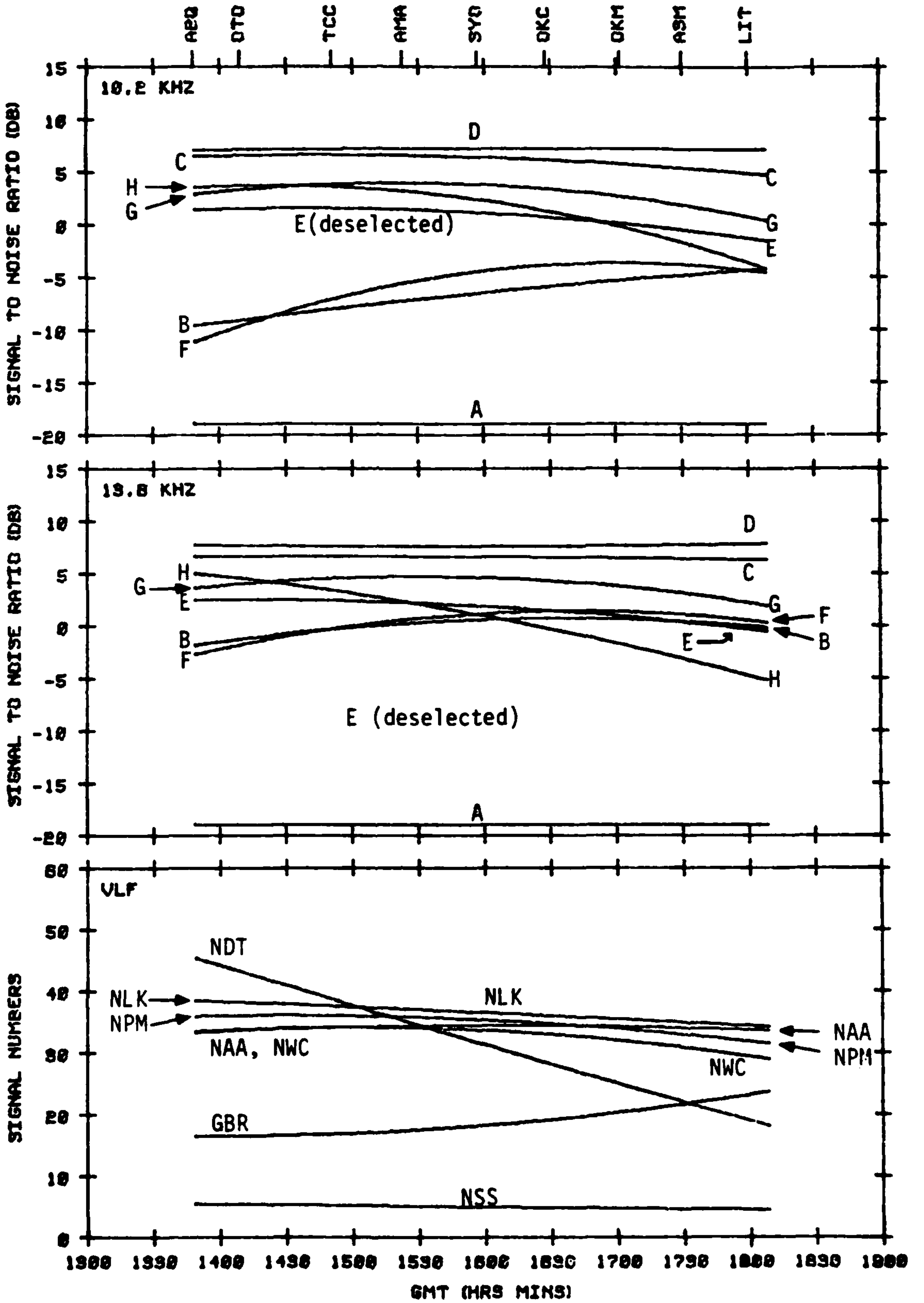


Figure 6.12 CONUS Omega/VLF Signal Coverage for Segment 12, Albuquerque, NM to Little Rock, AR (May 16, 1983)

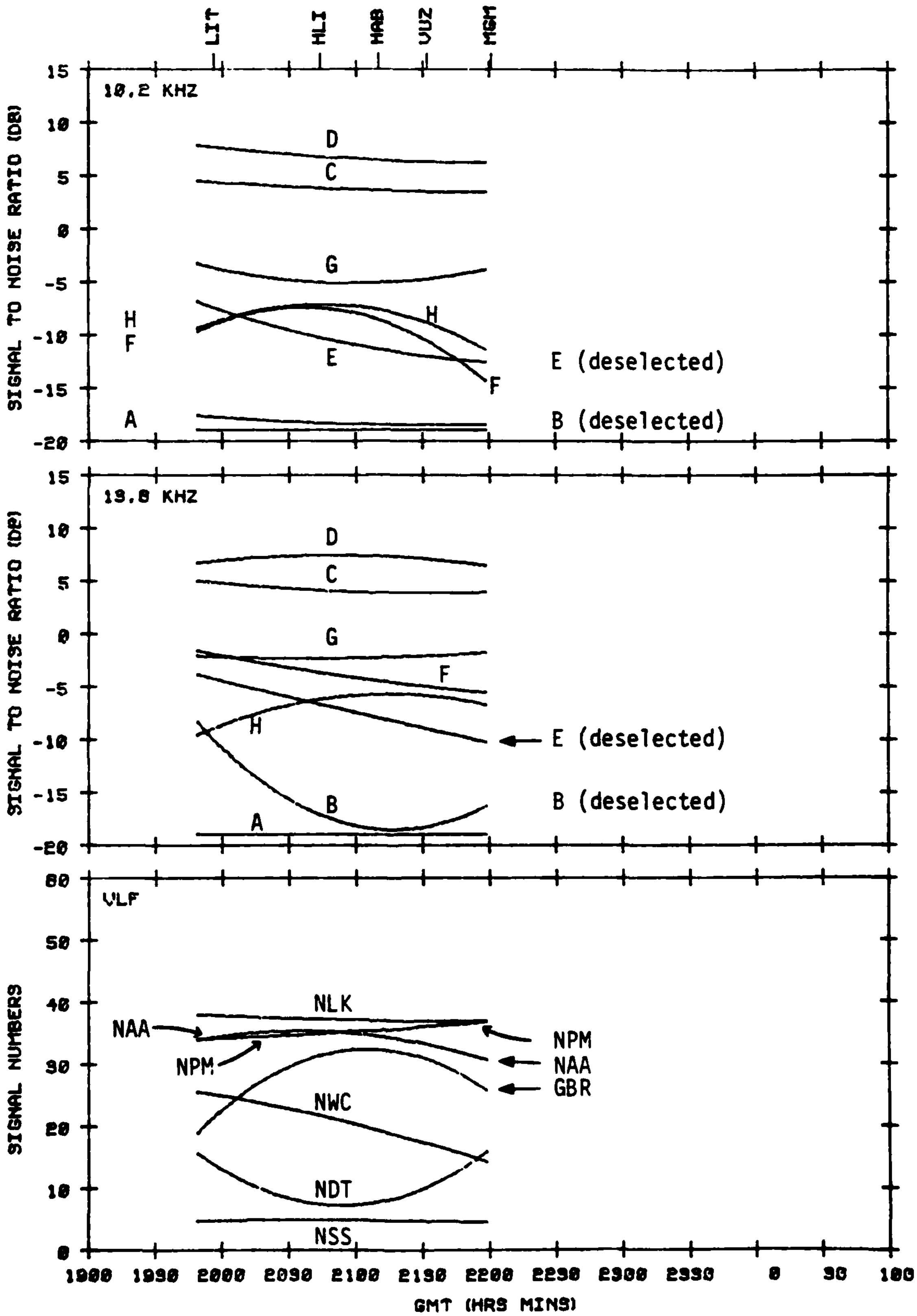


Figure 6.13 CONUS Omega/VLF Signal Coverage for Segment 13, Little Rock, AR to Montgomery, AL (May 16, 1983)

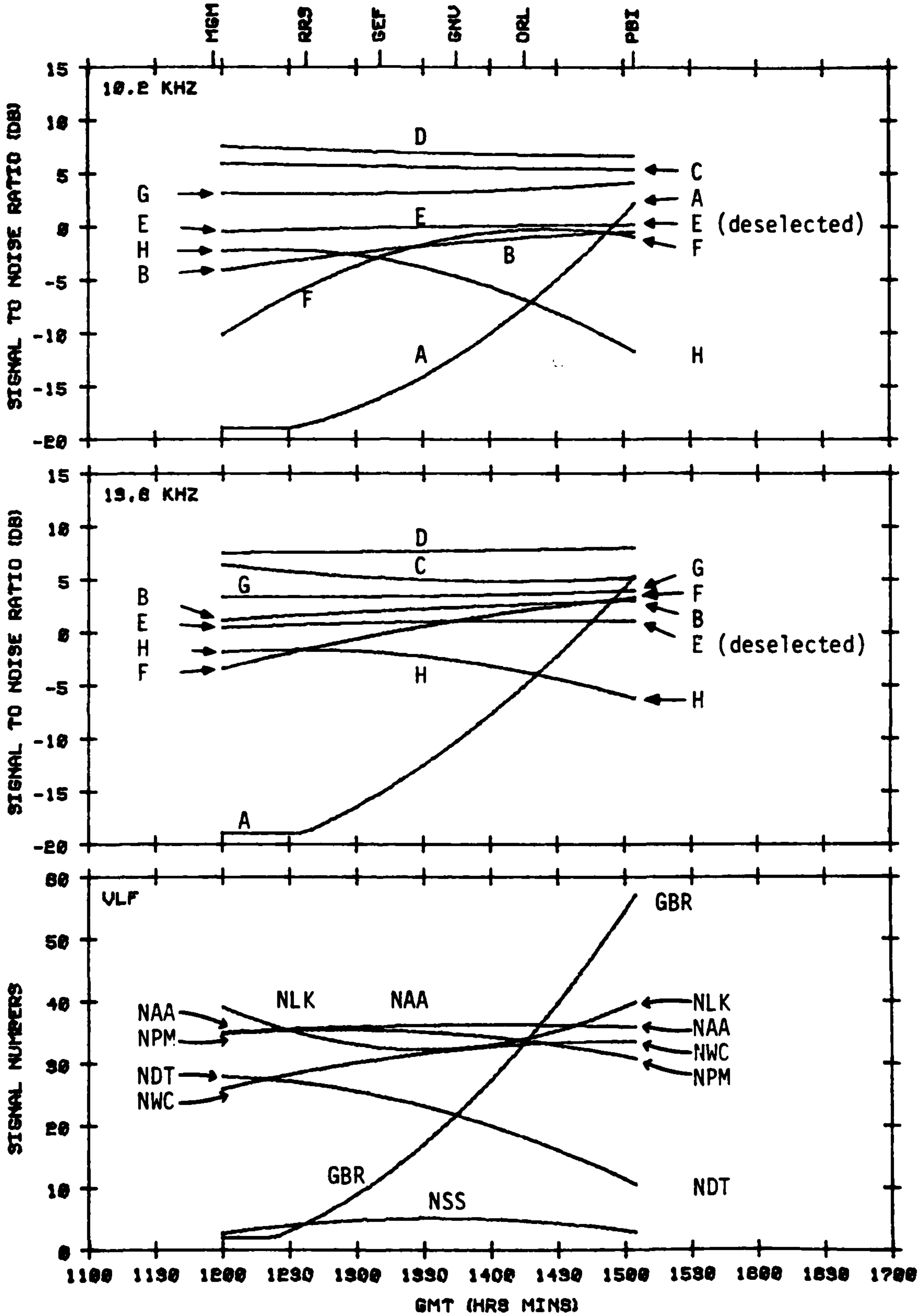


Figure 6.14 CONUS Omega/VLF Signal Coverage for Segment 14, Montgomery, AL to Palm Beach, FL (May 17, 1983)

Table 6.1 VOR/VORTAC Stations Used During Omega/VLF Data Collection Flights

IDENTIFIER	LOCATION	IDENTIFIER	LOCATION
ABQ	Albuquerque, NM	JAX	Jacksonville, FL
ALD	Allendale, SC	LIN	Linden, CA
AMA	Amarillo, TX	LIT	Little Rock, AR
AUW	Wausau, WI	LWS	Lewiston, ID
AXN	Alexandria, MN	MFR	Medford, OR
BFL	Bakersfield, CA	MGM	Montgomery, AL
BGM	Binghamton, NY	MKG	Muskegon, MI
BIL	Billings, MT	MLS	Miles City, MT
BIS	Bismarck, ND	MSO	Missoula, MT
CAE	Columbia, SC	OKC	Oklahoma City, OK
DIK	Dickinson, ND	OKM	Okmulgee, OK
DLS	Dalles, OR	ORL	Orlando, FL
DQO	Dupont, DE	OTO	Otto, NM
DRU	Drummond, MT	OTT	Nottingham, MD
EAU	Eau Claire, WI	PBI	Palm Beach, FL
EED	Needles, CA	PDX	Portland, OR
EUG	Eugene, OR	PMD	Palmdale, CA
FAR	Fargo, ND	PRC	Prescott, Az
FAT	Fresno, CA	PSC	Pasco, WA
FJS	Fort Jones, CA	RBL	Red Bluff, CA
FML	Fort Mill, SC	RIC	Richmond, VA
FNT	Flint, MI	RRS	Wiregrass, AL
FSM	Ft. Smith, AR	SAC	Sacramento, CA
GEF	Greenville, FL	SAV	Savannah, GA
GEP	Gopher, MN	SAX	Sparta, NJ
GNV	Gainesville, FL	SBJ	Solberg, NJ
GRB	Green Bay, WI	SBV	South Boston, VA
GSO	Greensboro, NC	SSI	Brunswick, GA
HAB	Hamilton, AL	SYO	Sayre, OK
HEC	Hector, CA	TCC	Tucumcari, NM
HLI	Holly Springs, MS	VUZ	Vulcan, AL
HLN	Helena, MT	YXU	London, CA
INW	Winslow, AZ	ZUN	Zuni, NM

STATION	OBSERVATION
	(continued)
D-North Dakota	Received throughout the flight area. Station was deselected when the aircraft was within 300 nm on Segments 4, 5, 6, 7 and 8.
E-LaReunion	Received throughout the eastern two thirds of the data collection area. Station was deselected throughout the area due to possible long path propagation.
F-Argentina	Generally received throughout the data collection area but was weak in the Pacific Northwest. The 13.6 kHz signal was noticeably stronger than the 10.2 kHz signal in this area. The signal was not received during the night flight of Segment 6.
G-Australia	Received throughout the data collection area. The signal was noticeably weaker during the night flight of Segment 6.
H-Japan	Received throughout the southern and western parts of the area. Received intermittently in the eastern and northern areas. The signal was noticeably weaker during the night flight of Segment 6.

6.1.2 VLF Signal Coverage

The following observations were made regarding VLF signal coverage shown in Figures 6.1 through 6.14:

STATION	OBSERVATION
NWC-Australia	Received in the western and southern parts of the data collection area. Not received during the night flight of Segment 6.
NDT-Japan	Received in the western and southern parts of the data collection area. Not received during the night flight of Segment 6.
GBR-England	Generally received in the eastern half of the flight area. Not received during the night flight of Segment 6.
NAA-Maine	Received throughout the area. NAA would be deselected in the northern New England area.

STATION	OBSERVATION
	(continued)
NPM-Hawaii	Received throughout the data collection area.
NSS-Maryland	Only on the air one day during the test (6-15-83) and was received in the western states that day.
NLK-Washington	Received throughout the data collection area but was deselected when the aircraft was within 300nm on Segments 9 and 10.

6.1.3 Signal Coverage Summary

The Omega/VLF navigation system provided adequate signal coverage for most of the flight test with one noticeable exception - the night flight in the north central part of the United States. During that period four Omega and three VLF signals were received. Of the four Omega signals, North Dakota was deselected due to modal interference conditions. Of the remaining three Omega signals (i.e. Hawaii, Japan and Australia) Hawaii and Australia arrived from nearly the same direction and produced poor fix geometry and high geometric dilution of precision (GDOP). In addition, Japan and Australia signals exhibited poor to fair signal-to-noise ratios.

The three VLF signals that were available were Washington, Maine and Hawaii. The Washington and Hawaii VLF signals arrived from the same direction as the Hawaii and Australia Omega signals and the Maine VLF arrived from a direction approximately opposite the Omega signals. Consequently, the VLF signals did not significantly improve the poor GDOP conditions.

The VLF signal from NSS in Maryland would have improved GDOP somewhat in the North Central area if it had been transmitting. However, the VLF stations are operated by the U.S. Navy for communication purposes and are not intended for navigation and therefore cannot be relied upon for this purpose. Additional quantitative discussions of the effect of station reception on GDOP in this area are found in Section 6.3.2.1.

6.2 DME POSITIONING SYSTEM PERFORMANCE

During most enroute segments of the flights, four to six DME distance values were recorded. On takeoff and landing and in a few areas in Montana and Oregon there were periods when fewer than three DME distances were available. Since there were ample stations with suitable geometry in most areas of the flights, reception of signals from at least three DME stations with suitable geometry was established as a minimum criterion for acceptance of a DME derived aircraft position.

At locations where three or more measurements were used to establish the aircraft position, the root mean square value of the DME residuals usually provided an effective means for identification and rejection of

occasionally erroneous DME data. When a large residual error was observed, the station with the largest error was dropped from the positioning solution and a new position solution was obtained. If the new solution met accuracy criteria it was accepted and the dropped station was flagged. This procedure provided an effective means of identifying position errors in the DME station data base.

Bias errors in the DME measurements, caused by transponder delay errors, also affected the accuracy of the DME positioning system. Those biases were estimated in instances where multiple stations were received and the estimates used to improve the position fixing accuracy. Since the DME positioning system was considered to be sufficiently accurate to establish the enroute performance of the Omega/VLF system, no effort was made in the data reduction process to reduce position errors caused by DME bias errors.

On some occasions the data collector would not record updated DME records. In these instances no position solution could be derived for the specified data record. This situation accured on about 6% of the records during the flight. These records were dropped from the analysis due to lack of position data.

The overall availability of satisfactory DME derived position was 84.4%. Most segments had an availability of 85% to 90%. The two segments with the lowest availability were Missoula, Montana to Eugene, Oregon (54.8%) and Eugene, Oregon to Fresno, California (74.8%). Availability on all other segments exceeded 80%.

6.3 OMEGA/VLF SYSTEM PERFORMANCE

The performance of the Omega/VLF system was based primarily upon three factors:

1) the operational evaluation of the system by the flight crew
2) the availability of navigation information
3) the accuracy and character of navigation information

The operational evaluation is contained in Section 5; the availability accuracy and characteristics of the navigation information are presented in this section.

6.3.1 System Availability

On twelve of the fourteen flight segments, Omega/VLF navigation information was available 100% of the time. The two noteable exceptions occured on May 10, 1983 at 1535 hours GMT upon descent to land at Flint, Michigan and on May 13, 1983 at 1840 hours GMT enroute near Fargo, North Dakota. On these occasions the system flag came on and indicated that navigation was unreliable.

In both instances the system failed to resynchronize and navigation information was unavailable for the remainder of the flight. At Flint,

this was a period of twelve minutes prior to landing. At Fargo, the system was unavailable for two hours and thirty nine minutes. The crew did not have time to update the aircraft position through the Omega/VLF control display unit at Flint due to cockpit workload in the approach phase of flight. Several attempts at updating aircraft position were attempted in the May 13th flight. None of the attempts were successful in reestablishing valid navigation information.

During both periods of system unavailability, the navigation warning flag was in full view on the aircraft course deviation indicator. Thus, the crew knew the navigation information was unreliable and unsuitable for providing guidance.

The manufacturer's engineering representatives were asked about possible causes for the loss of navigation. They indicated that the two most common causes of loss of navigation are precipitation static affecting the antenna, and power interruption to the navigation system receiver/processing unit. In precipitation static situations the receiver clock remains synchronized and navigation is usually restored when the precipitation static conditions subside. If power is interrupted for longer than seven seconds, synchronization may be lost and the system will require additional time to reacquire navigation and accuracy may be seriously affected depending upon the quality of the position updates provided by the flight crew.

The representatives were also asked if the lack of airspeed inputs to the system would affect the ability to reacquire navigation. They indicated that not having airspeed information available could affect the system accuracy upon reacquisition, but should not affect the systems ability to resynchronize and reacquire the Omega/VLF signals.

In reviewing the recorded data, a shift in Omega/VLF values for GMT relative to the time base in the data collector was noted in both instances of signal loss. At Flint a twenty-eight second shift was noted and at Fargo a seven second shift was observed. This shift, a delay in the navigation system clock, and the difficulty in reacquiring navigation in both instances, would tend to support the power interruption cause for loss of navigation. However, the flight crew observed no conditions that would support loss of power to the unit.

6.3.2 System Accuracy

Omega/VLF system accuracy was derived from the data recorded by the data acquisition system and processed according to the methods described in Section 4. Position derived from the scanning DME system was used as the aircraft reference standard. The accuracy analysis provided the following measures of system performance:

Total system crosstrack error - based on the reference system position relative to desired aircraft track.

Total system alongtrack error -	based on a comparison of the Omega/VLF distance to waypoint versus the reference system derived distance to waypoint.
Navigation system error -	based upon a comparison of the Omega/VLF derived latitude and longitude and the reference system derived latitude and longitude. Several measures of this error are contained in the data including root mean square radial error (DRMS), easting error, northing error, and navigation system alongtrack and crosstrack error (easting and northing error resolved in aircraft alongtrack and crosstrack coordinates).
Navigation computer error -	based on a comparison of distance to waypoint and crosstrack deviation derived from the Omega/VLF position and desired track and distance to waypoint and crosstrack deviation output by the navigation system.
Flight technical error -	based on the course deviations observed on the signal to the pilot's course deviation indicator.

The recorded data were processed at ten second intervals which is also the repetition interval of the Omega signal format. Some of the data appeared quite noisy since little or no filtering was provided due to the slow Omega repetition frequency. The resolution of the data also contributes to quantization of the accuracy data. The following resolution limits were in effect:

latitude	-	0.1 arc minutes (.10 nm)
longitude	-	0.1 arc minutes (.07-.08 nm)
distance to waypoint	-	.10 nm
crosstrack deviation	-	.12 nm

Over the entire flight, accuracy data were available at 47% of the data records. Data were unavailable for reasons described in the following paragraphs.

The data were edited to delete portions of the flight when the Omega/VLF system was not being used for navigation. These include

situations such as terminal area maneuvering, ATC requested diversions from desired track and weather avoidance. Also included are those times when the aircraft was maneuvering to intercept a new course at route turn points.

Omega data provided by the receiver/processor was unavailable at about 20% of the ten second data records. In addition, DME position data was not available at about 15% of the data records (as discussed in Section 6.2). Also, no data were processed during the two periods of system non-availability at Flint and Fargo.

6.3.2.1 Navigation System Accuracy

The navigation system accuracy was established by comparing Omega/VLF latitude and longitude data with similar data derived from the scanning DME reference standard. Plots of the root mean square radial error (DRMS) derived from this position comparison are shown in Figure 6.15 through 6.28 for the fourteen segments flown during the flight test. Due to the resolution of the data and the lack of filtering the data appear noisy and contain numerous "spikes" due to position changes caused by signal phase fluctuations and Omega/VLF stations being added or dropped from the position solution.

For most of the segments DRMS errors are small to moderate and range between 0.5 and 1.5 nm. Three exceptions to this generalization are the segment flown on May 9, 1983 (1245-1550 hours GMT) from Palm Beach, Florida to Columbia, South Carolina; the segment flown on May 10, 1983 (1730-2015 hours GMT) from Flint, Michigan to St. Paul, Minnesota; and the night flight segment on May 14, 1983 (0140-0340 hours GMT) from Bismarck, North Dakota to St. Paul, Minnesota.

On the 9 May flight, the error was about 2 nm for the first one and one-half hours then increased suddenly to about 3 nm at about 1420 hours GMT. On the 16 May flight the error rapidly diminished at 1420 hours from 3.5 nm to 2 nm. No obvious reason for these changes in error was apparent as the stations used for position determination did not change at this time. One possible explanation is propagation model error due to the transition of the Hawaii signal from a mixed day-night path to an all daylight path. However, these errors were not observed at 1420 hours GMT on Segments 3, 7 and 14. The segment flown on 10 May contained a large error between 1840 and 1900 hours GMT. This time coincided with the time that Liberia was transitioning to sunset at which time that station was deselected. Improvement in accuracy coincides with this deselection time.

The large errors observed on the night flight of 14 May (actually the evening of 13 May local time) was expected considering the stations received and their relative geometry (see discussions in Section 6.1). In this area three Omega stations are being received; Hawaii, Australia and Japan (North Dakota is deselected) with only Hawaii having a strong signal. Likewise, three VLF stations were received; NPM-Hawaii, NLK-Washington and NAA-Maine. The geometry of these stations was such that the crossing angles of the lines of position are very poor without some additional station with an east-west line of position. This

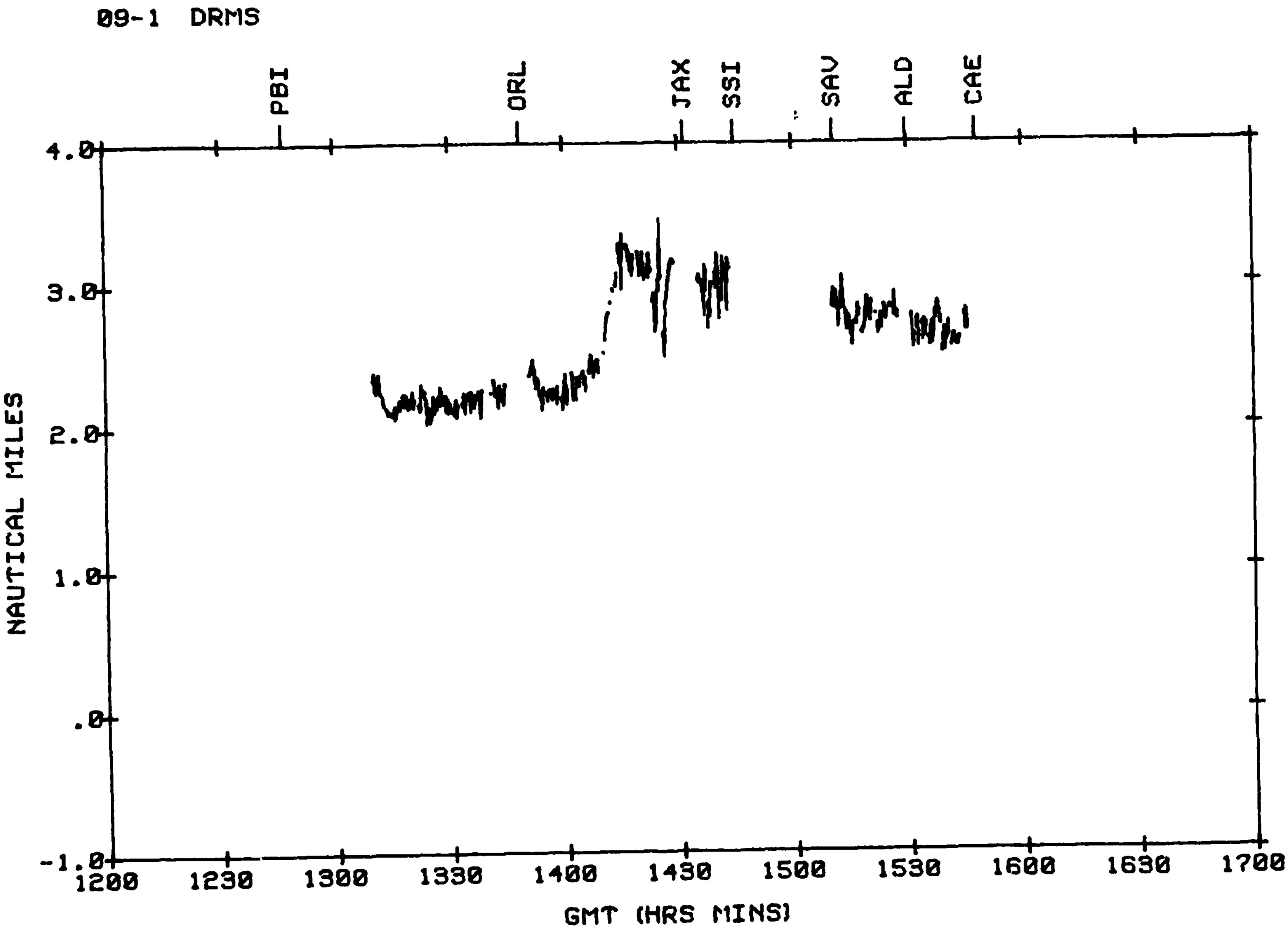


Figure 6.15 DRMS Error for Segment 1, Palm Beach, FL to Columbia, SC (May 9, 1983)

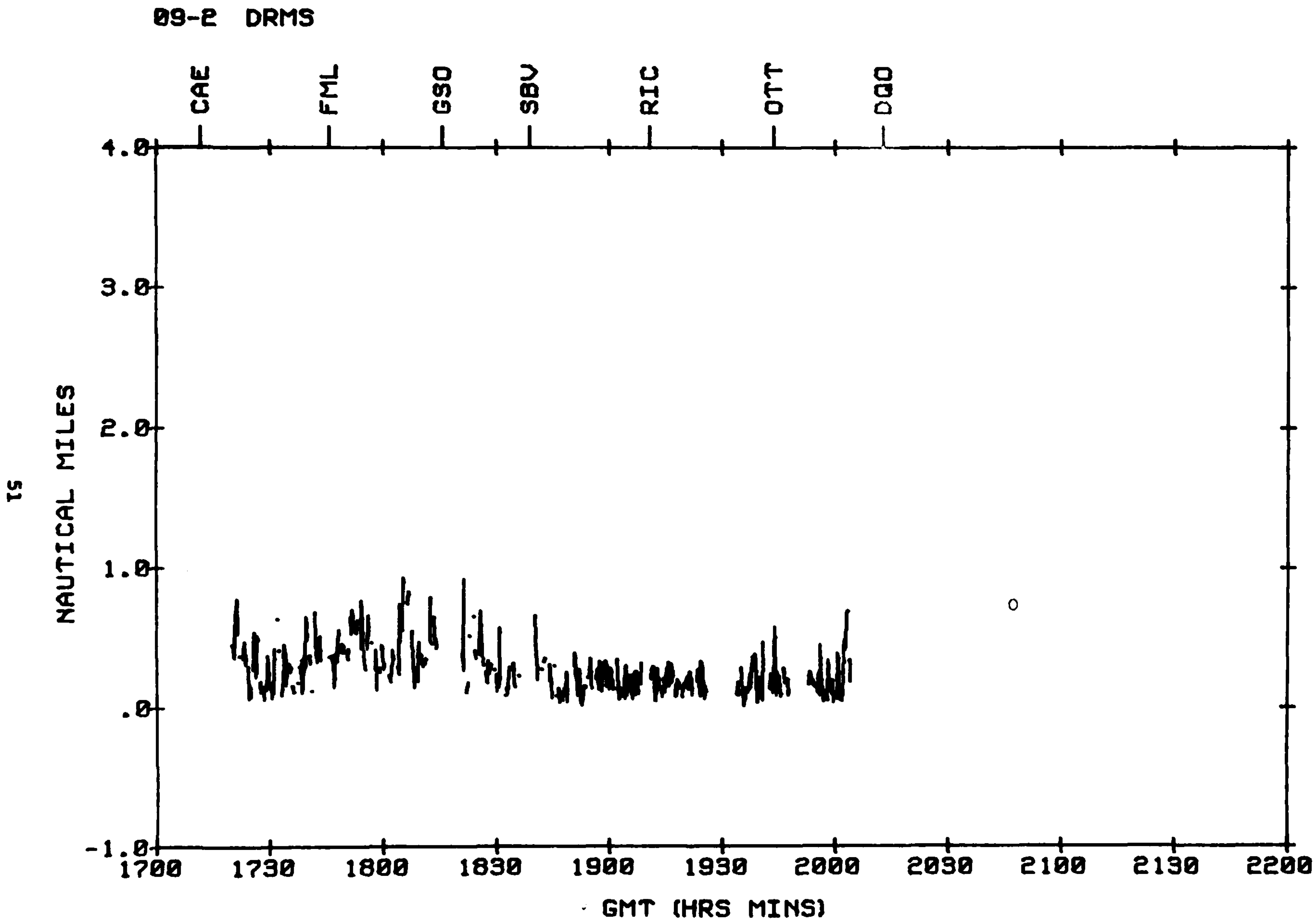


Figure 6.16 DRMS Error for Segment 2, Columbia, SC to Wilmington, DE (May 9, 1983)

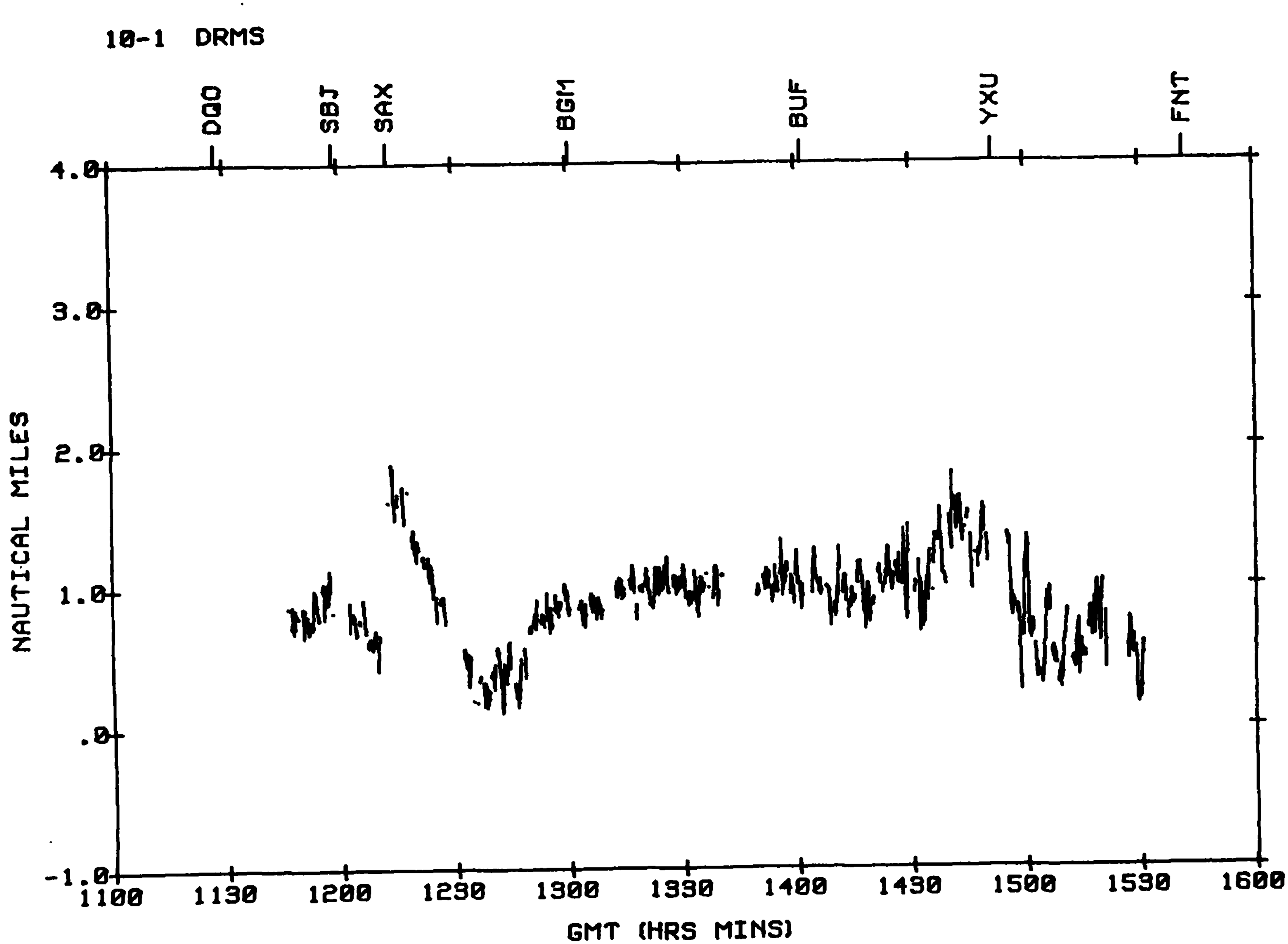


Figure 6.17 DRMS Error for Segment 3, Wilmington, DE to Flint, MI (May 10, 1983)

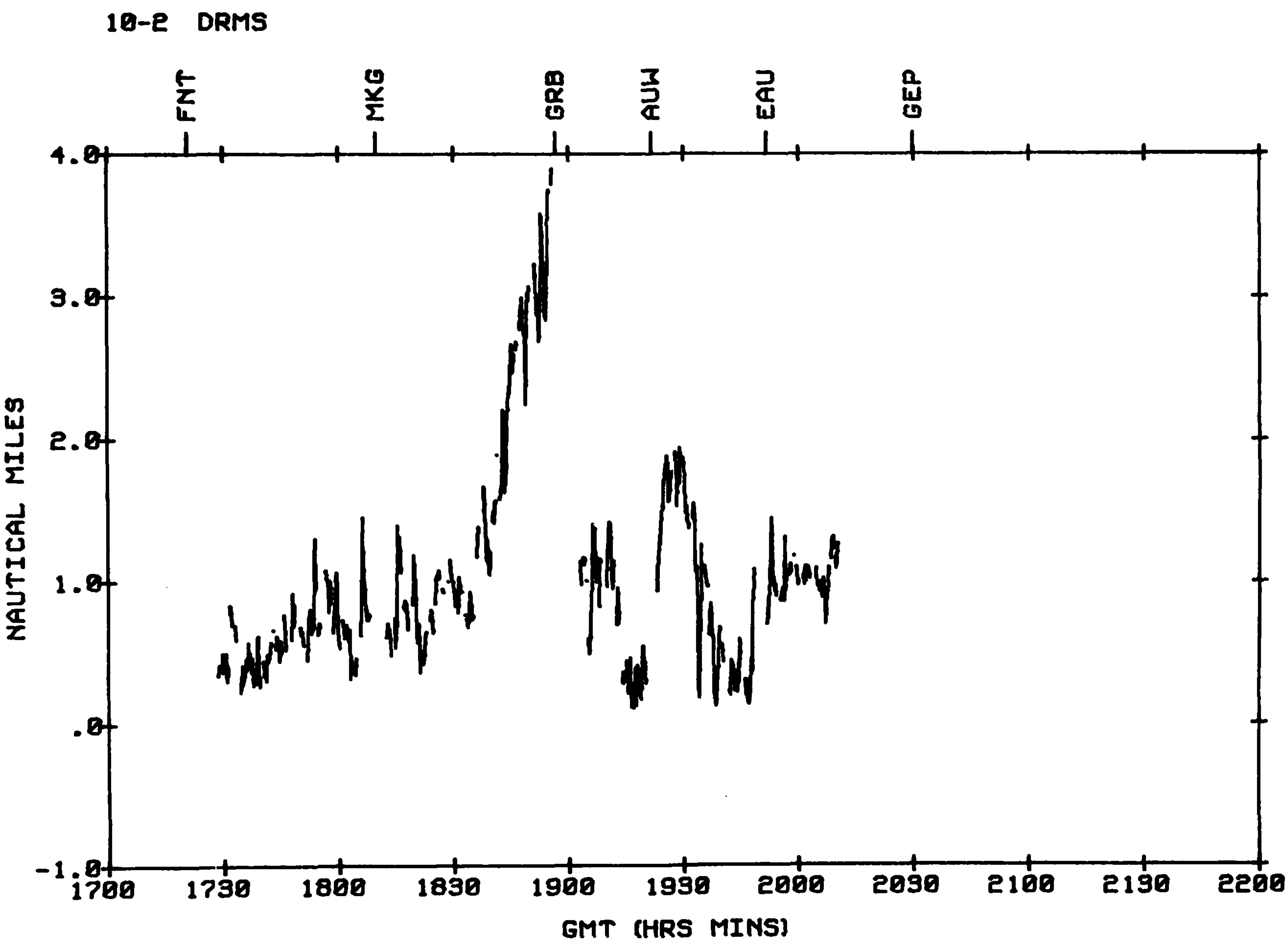


Figure 6.18 DRMS Error for Segment 4, Flint, MI to St. Paul, MN (May 10, 1983)

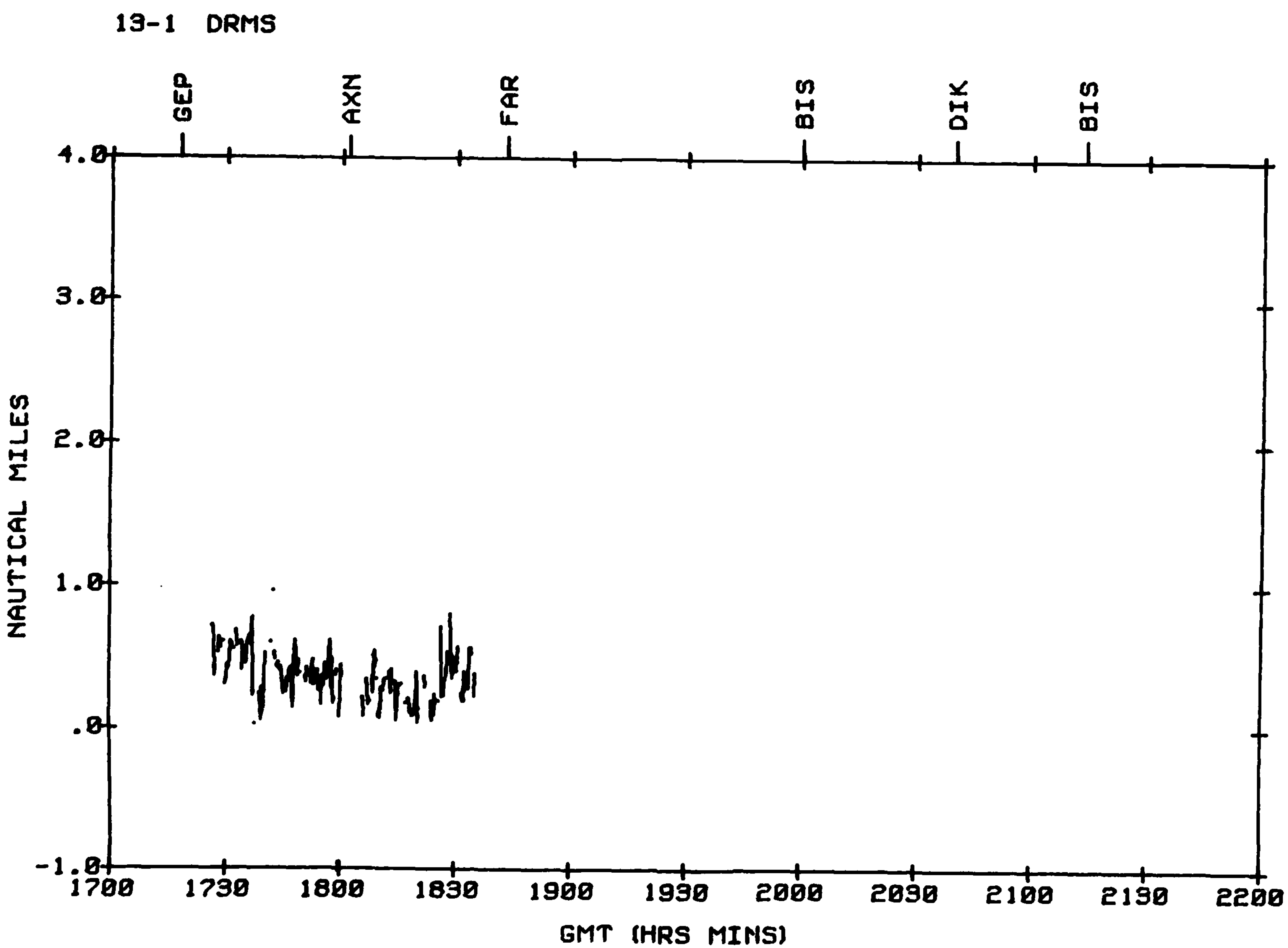


Figure 6.19 DRMS Error for Segment 5, St. Paul, MN to Bismarck, ND (May 13, 1983)

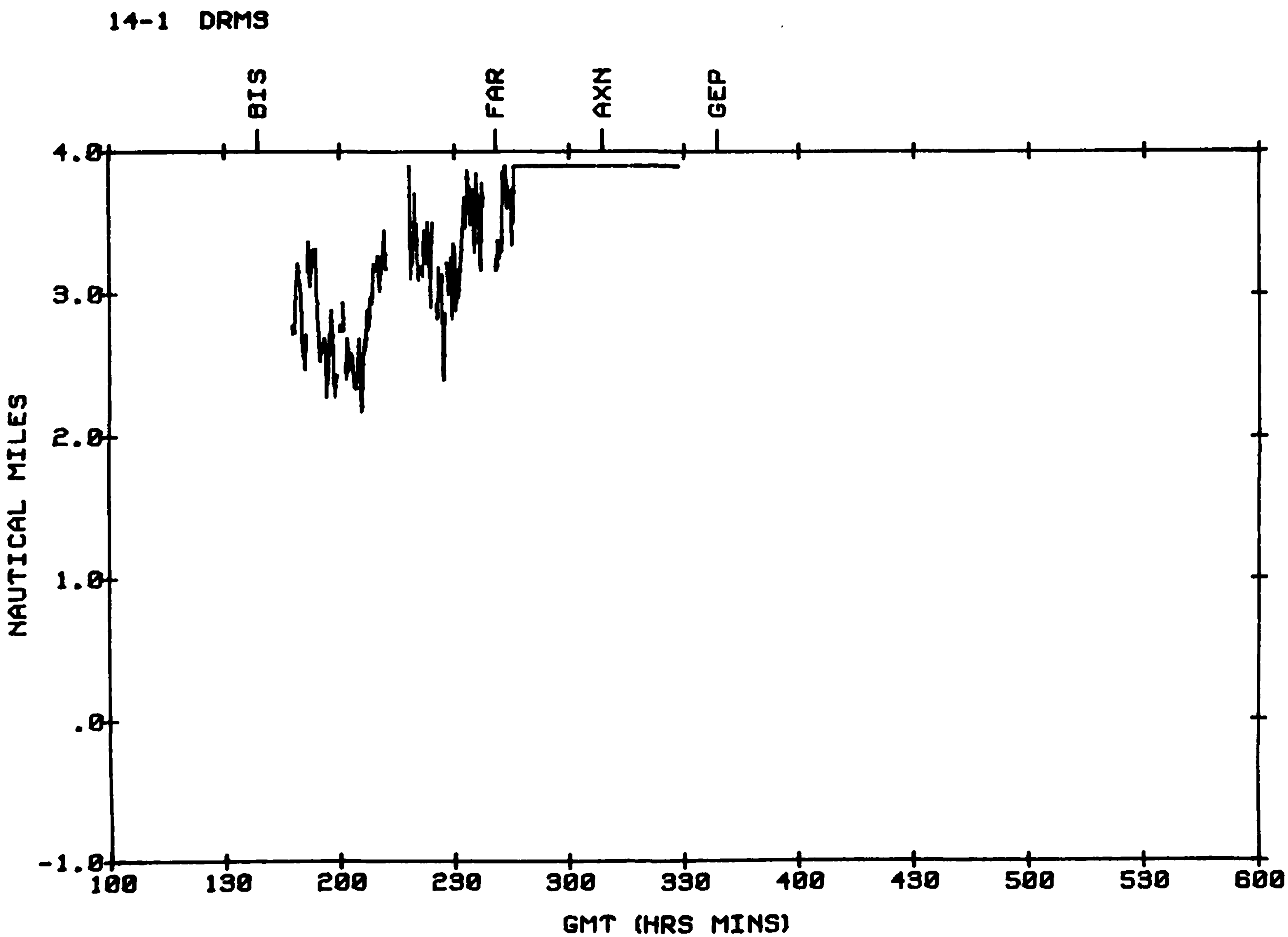


Figure 6.20 DRMS Error for Segment 6, Bismarck, ND to St. Paul, MN (May 14, 1983)

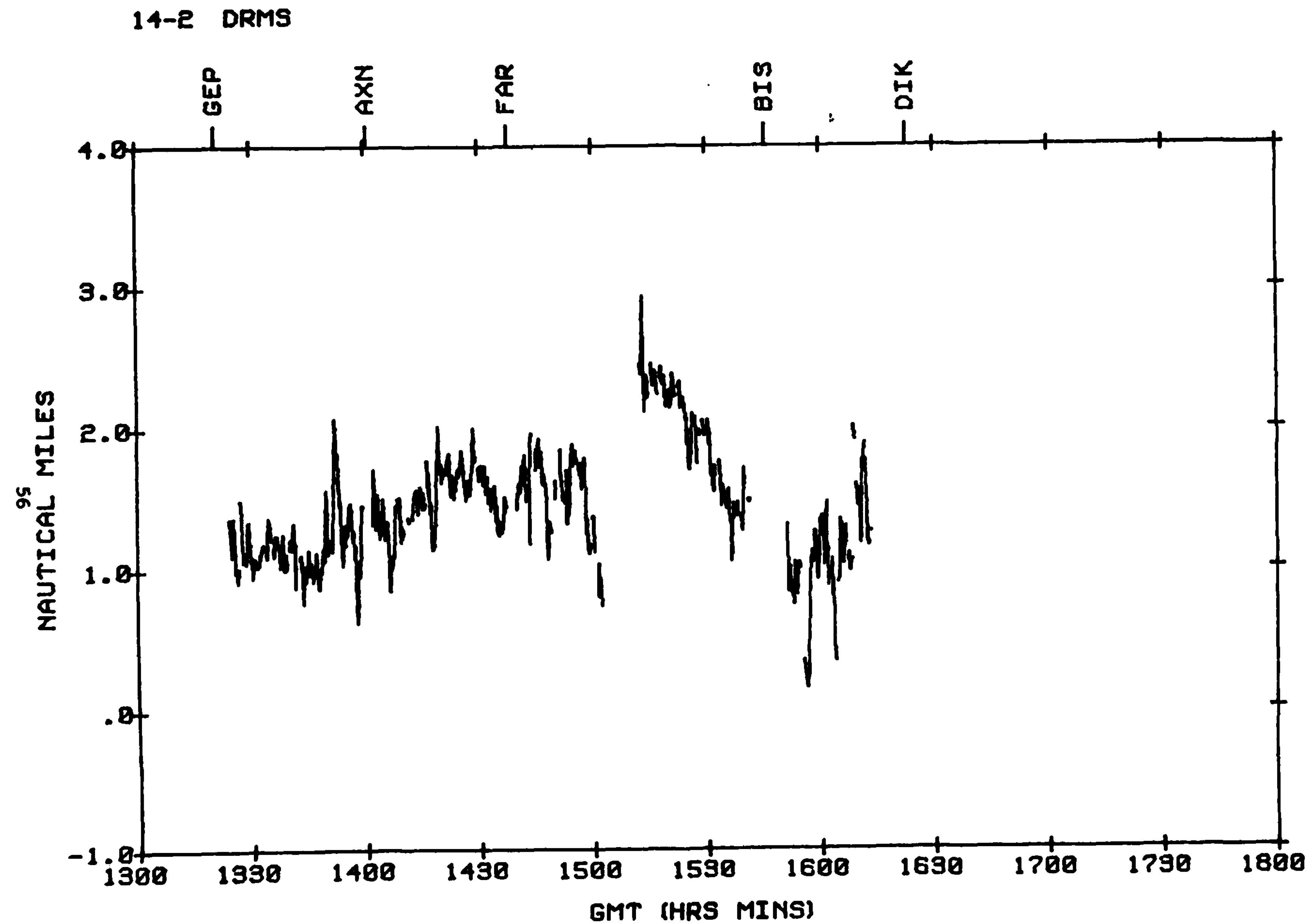


Figure 6.21 DRMS Error for Segment 7, St. Paul, MN to Dickinson, ND (May 14, 1983)

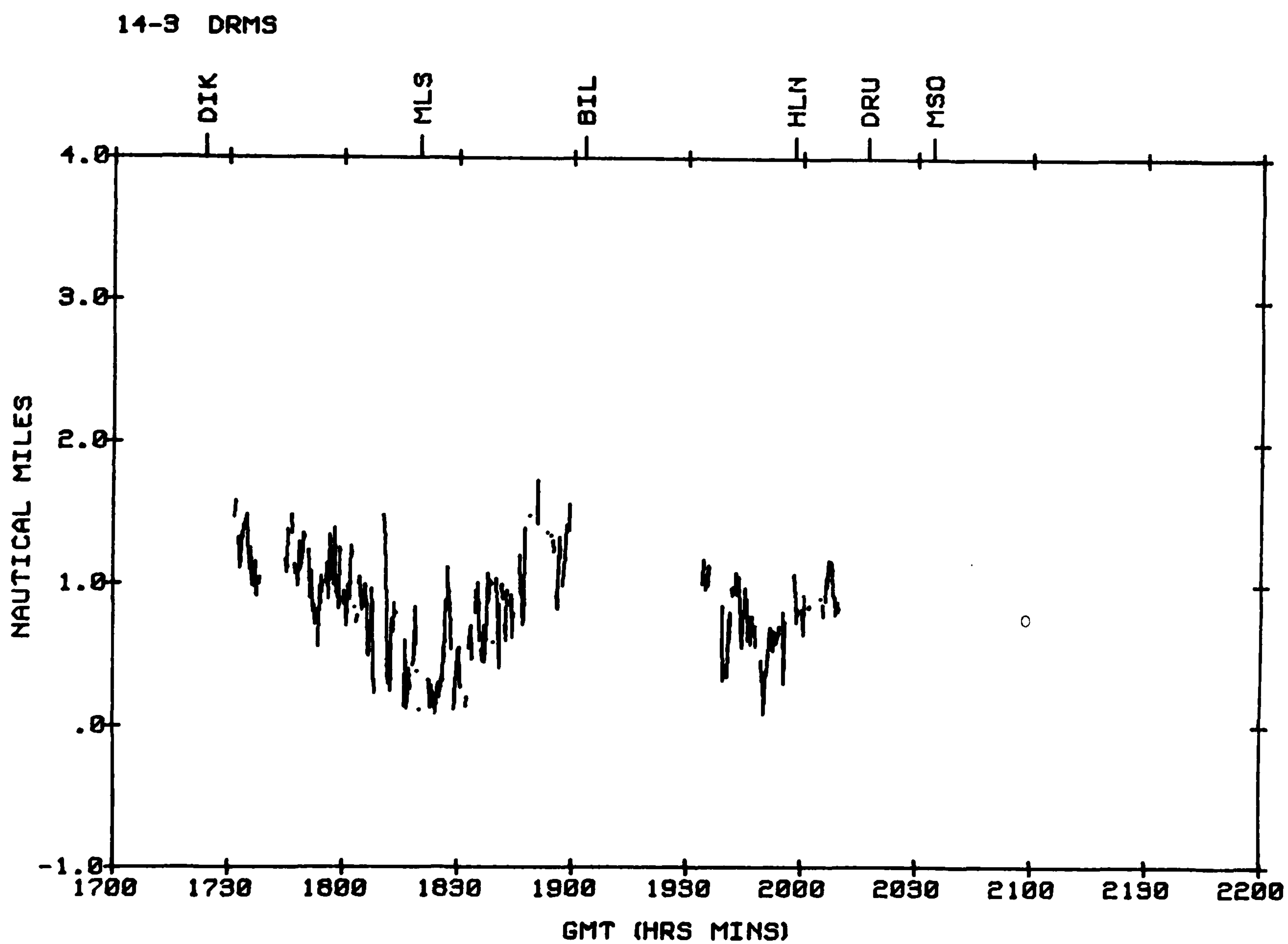


Figure 6.22 DRMS Error for Segment 8, Dickinson, ND to Missoula, MT (May 14, 1983)

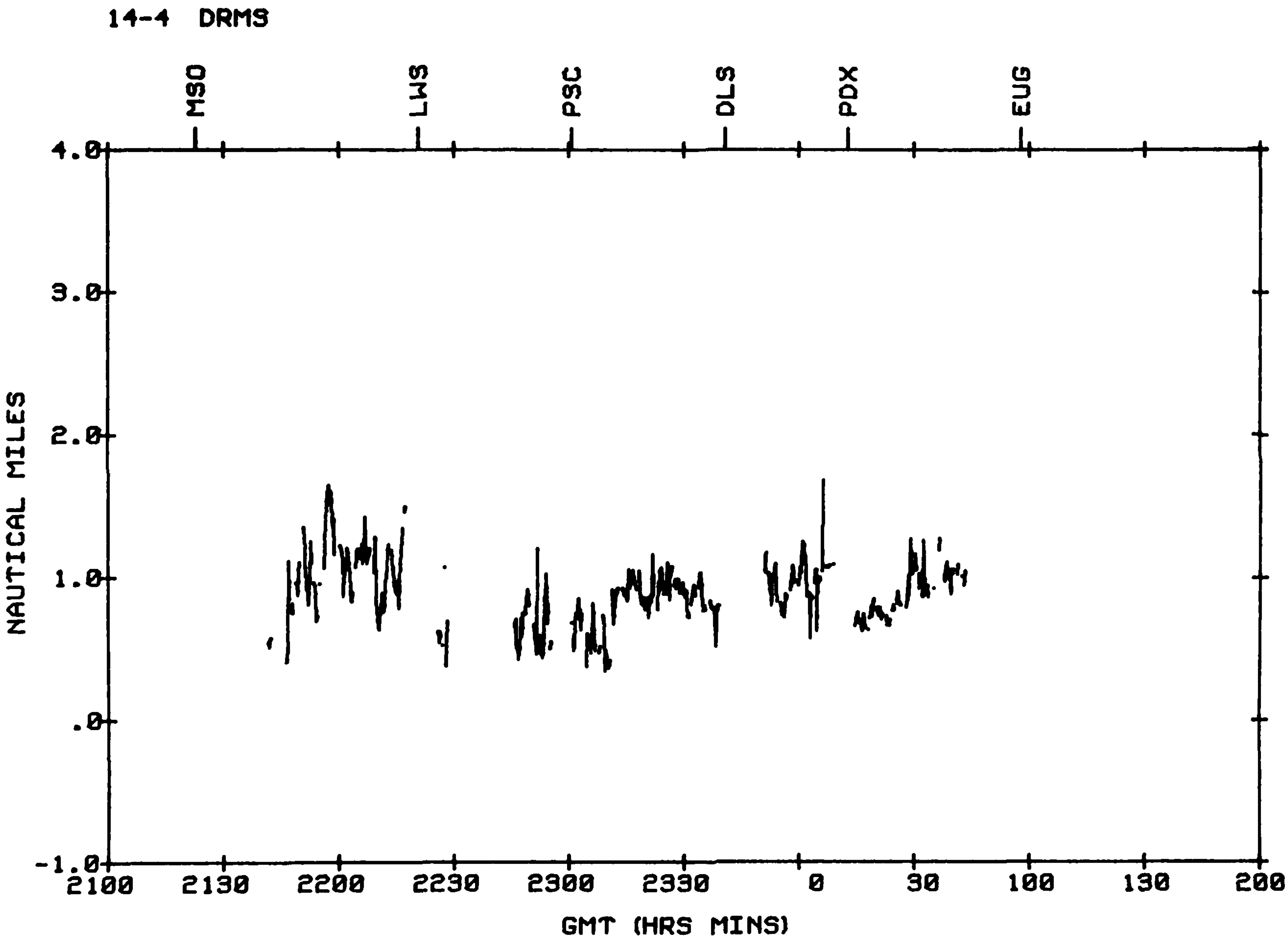


Figure 6.23 DRMS Error for Segment 9, Missoula, MT to Eugene, OR (May 14, 1983)

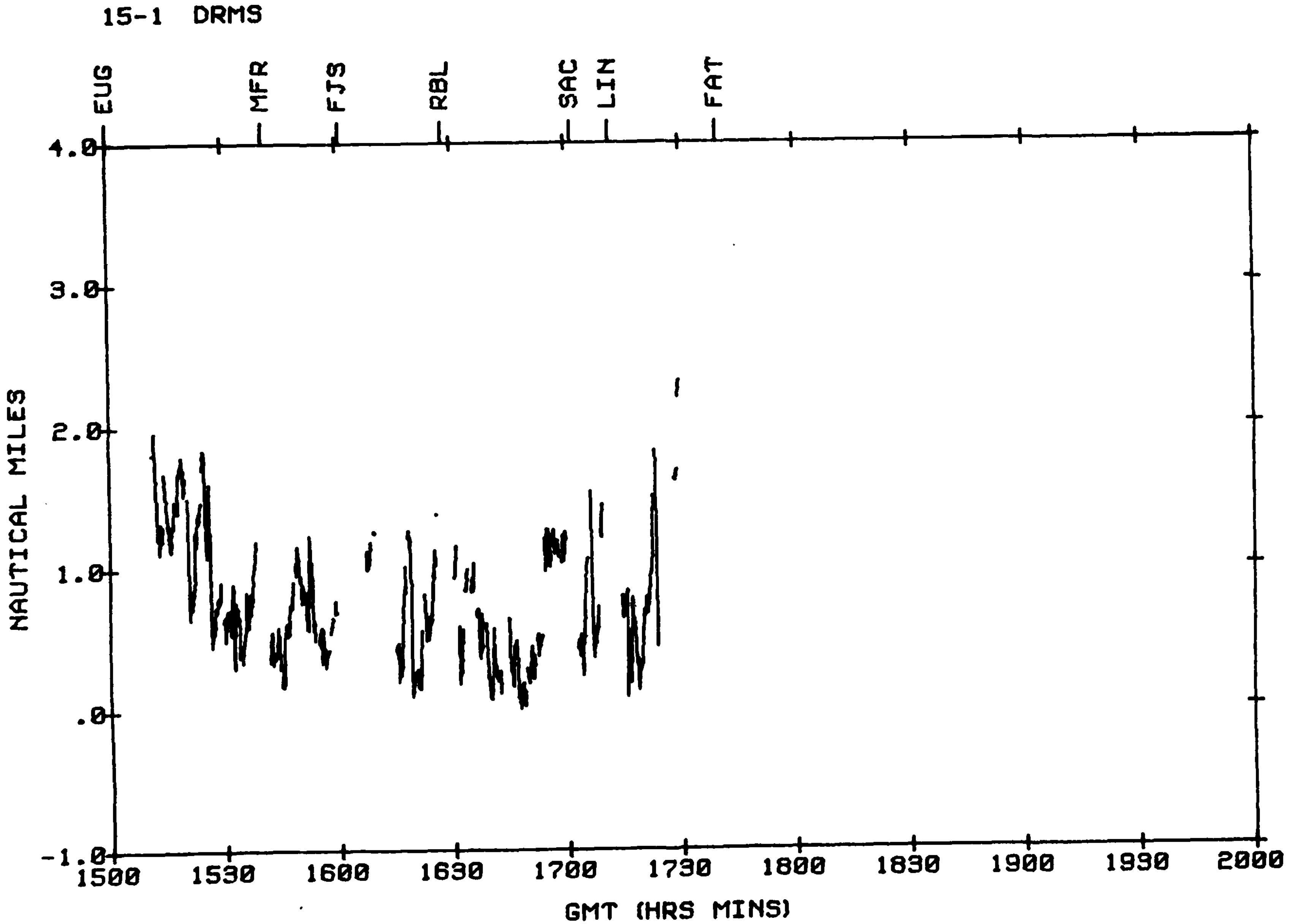


Figure 6.24 DRMS Error for Segment 10, Eugene, OR to Fresno, CA (May 15, 1983)

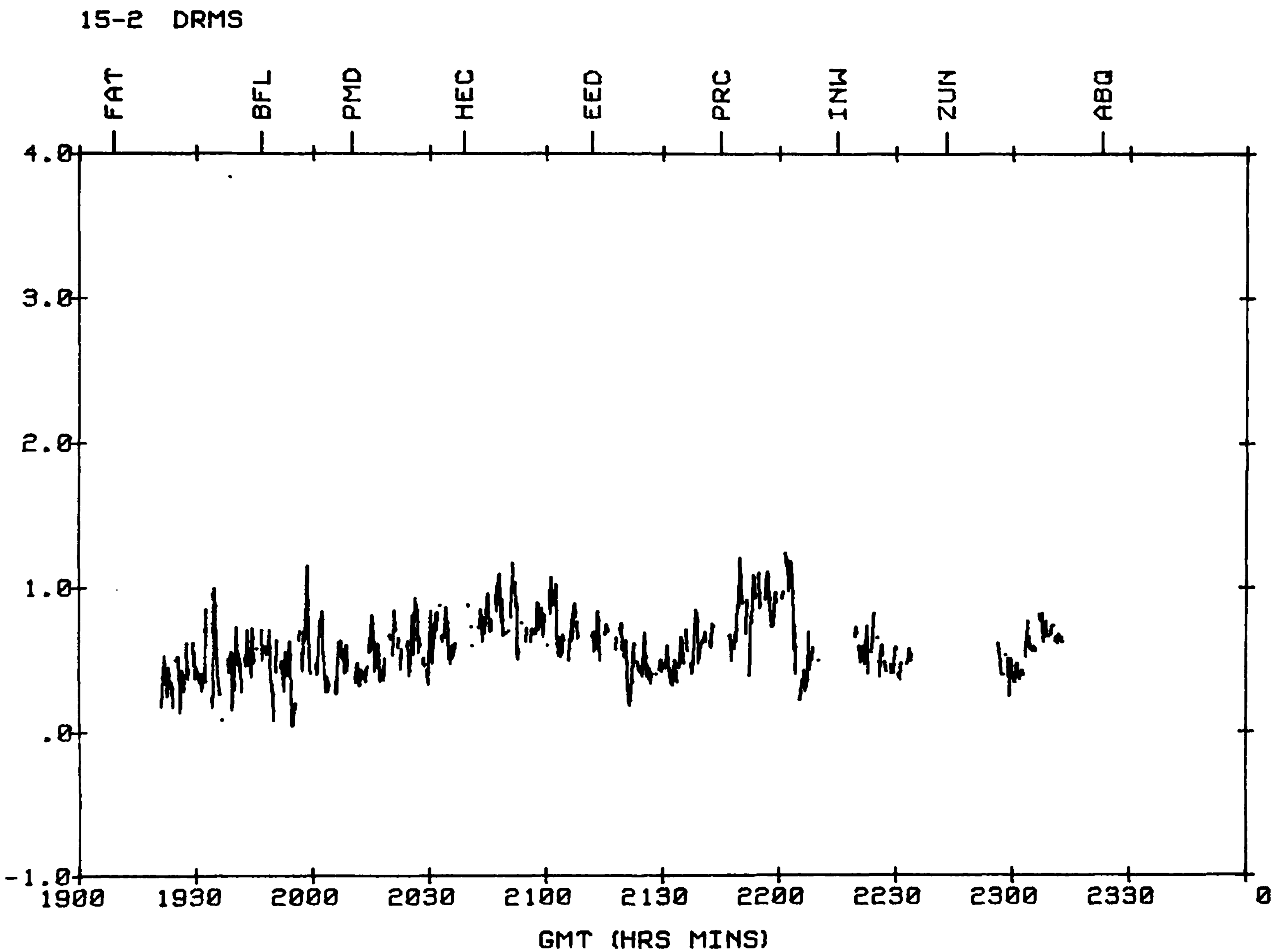


Figure 6.25 DRMS Error for Segment 11, Fresno, CA to Albuquerque, NM (May 15, 1983)

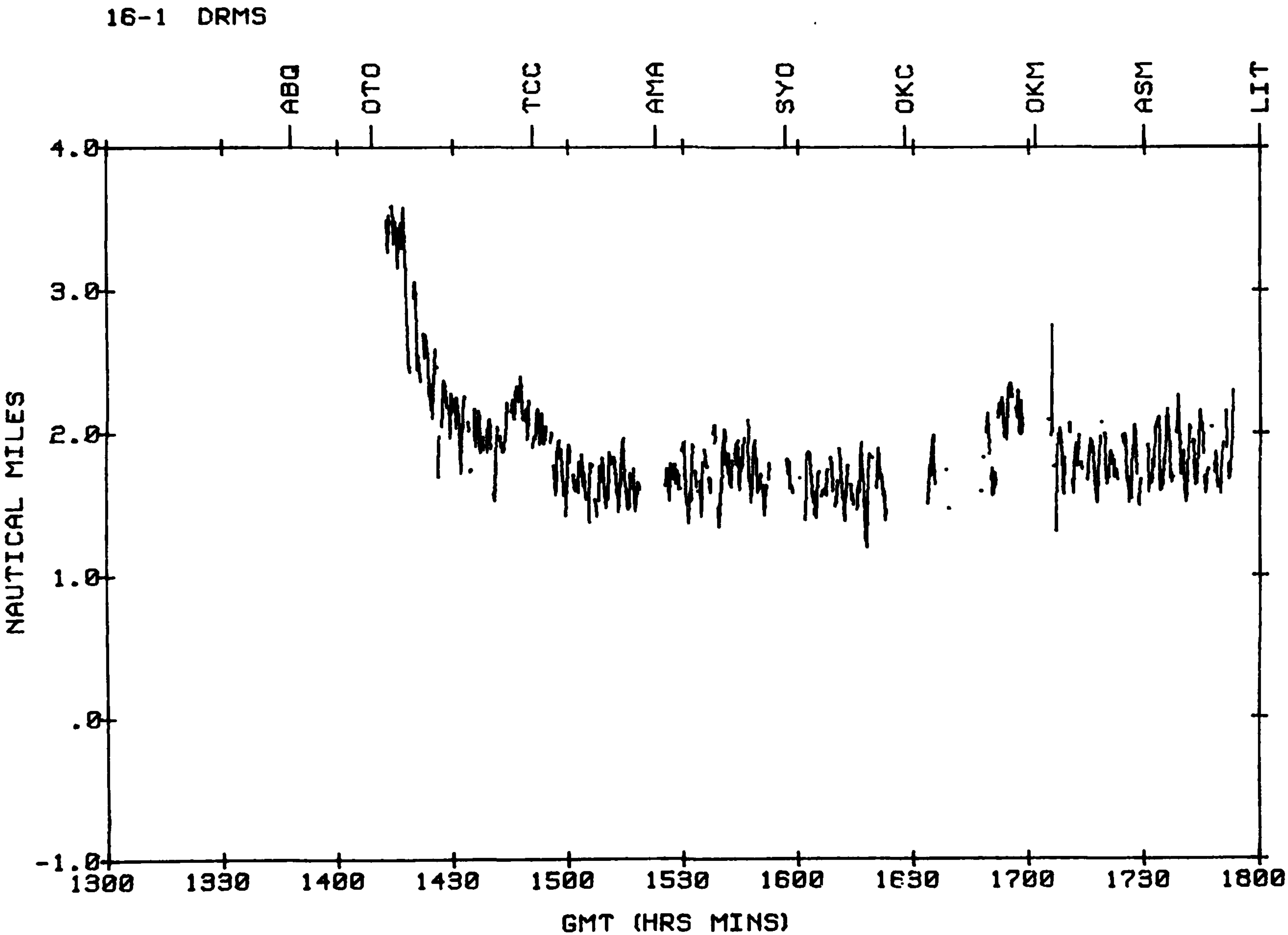


Figure 6.26 DRMS Error for Segment 12, Albuquerque, NM to Little Rock, AR (May 16, 1983)

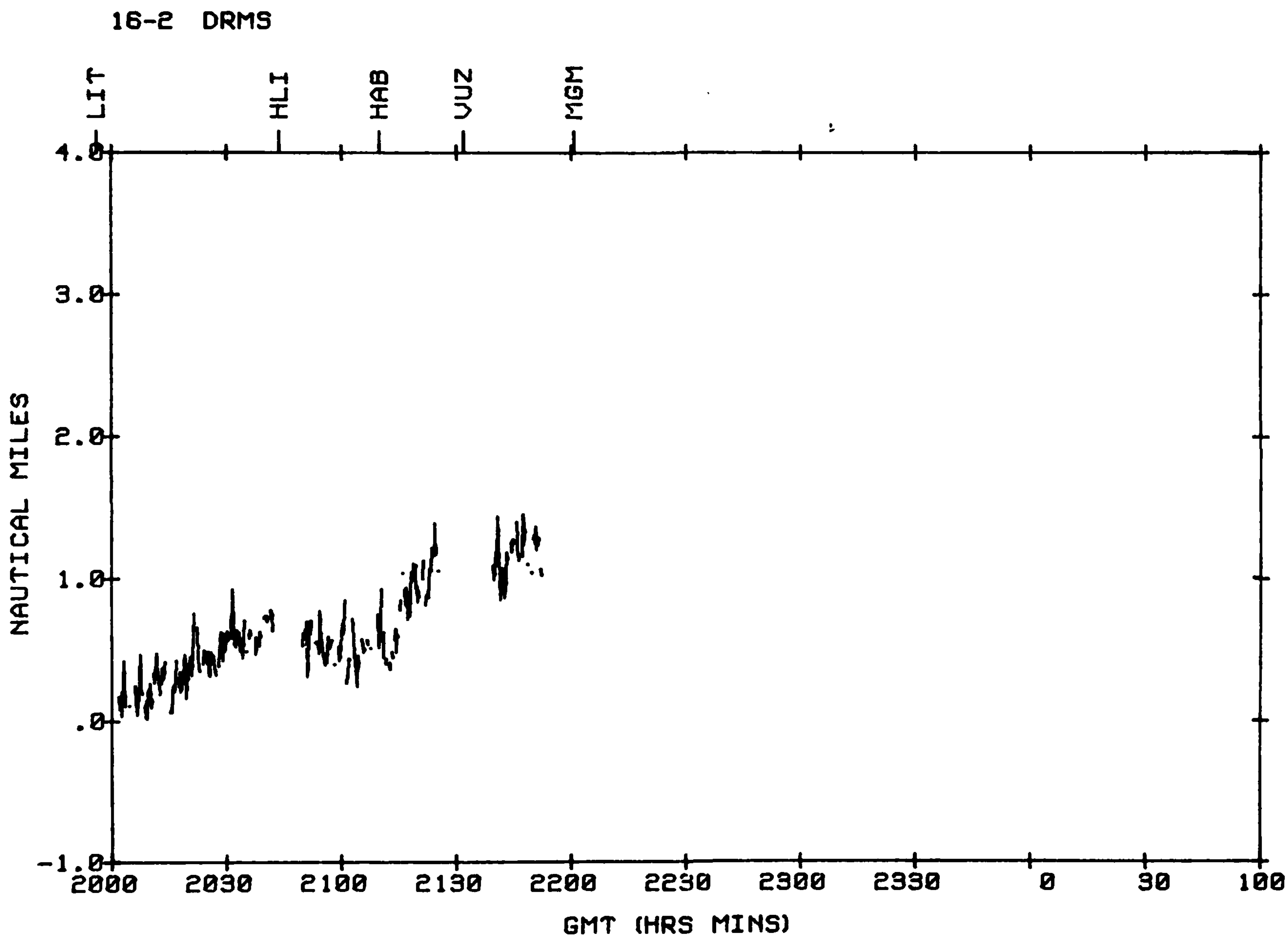


Figure 6.27 DRMS Error for Segment 13, Little Rock, AR to Montgomery, AL (May 16, 1983)

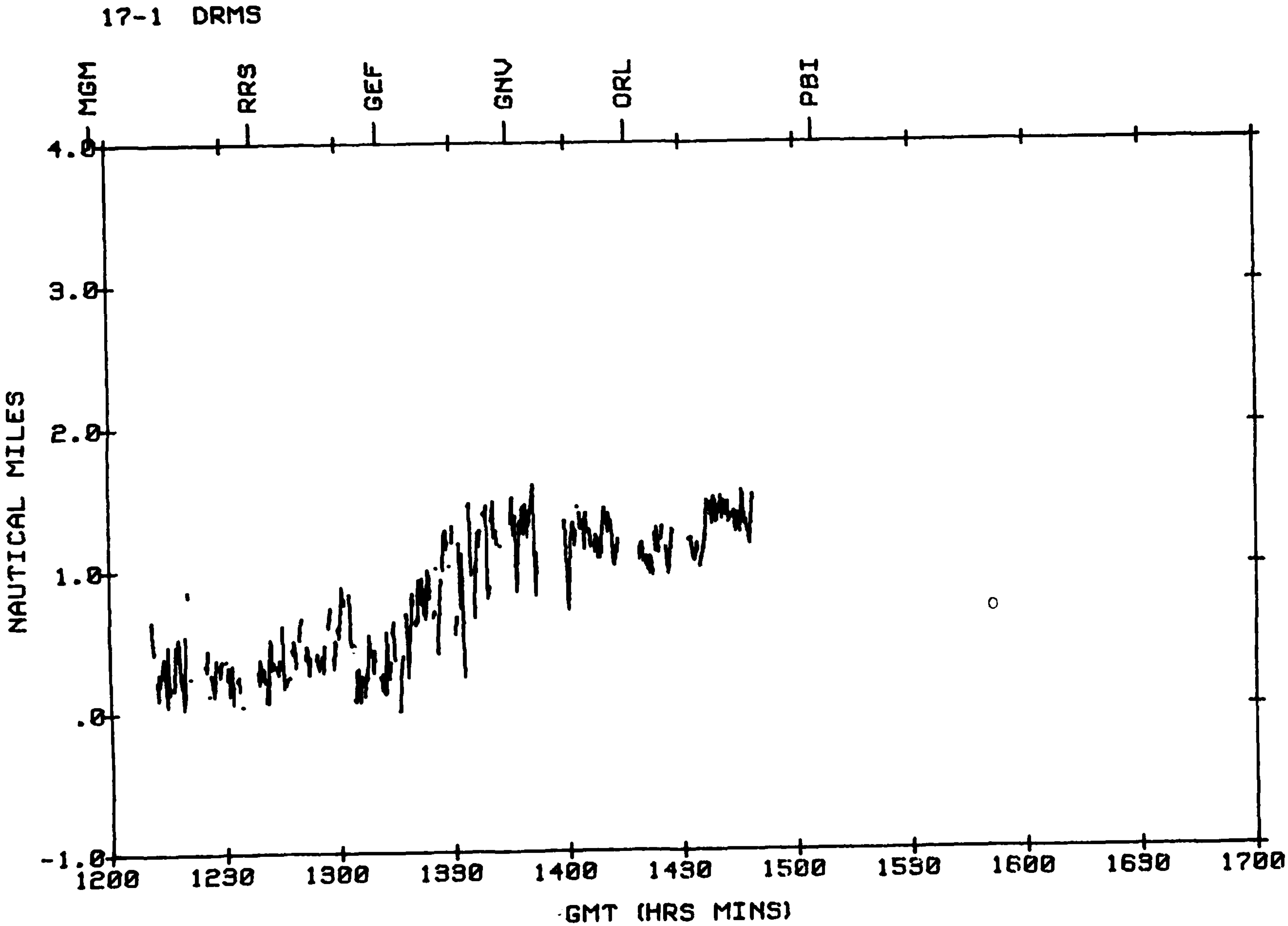


Figure 6.28 DRMS Error for Segment 14, Montgomery, AL to Palm Beach, FL (May 17, 1983)

situation would have been improved considerably if NAA-Maryland had been transmitting or if a strong signal from Japan was available. To illustrate this point, theoretical values of geometrical dilution of precision (GDOP) were calculated for several combinations of stations at Fargo, North Dakota. These values were derived using the GDOP Factor equation developed in Appendix A.

	RECEIVED STATIONS	GDOP FACTOR
Case A	Omega - Hawaii, Australia VLF - NPM-Hawaii, NLK-Washington, NAA-Maine	2.8
Case B	Same as Case A plus NSS-Maryland VLF Station	2.0
Case C	Same as Case A plus Japan Omega Station	1.2
Case D	Same as Case A plus Japan Omega Station and NSS-Maryland VLF station	1.1

It is evident from this geometric analysis that the availability of signals from either Japan, or NSS-Maryland, or both, is important in obtaining accuracy in the area where the North Dakota station is deselected.

6.3.2.2 Navigation Computer Accuracy

Statistical values for navigation computer error in alongtrack and crosstrack coordinates were evaluated for the fourteen flight segments. The errors were produced, to some extent, by filtering and smoothing of the Omega/VLF guidance data and were characteristically small.

The mean values and standard deviations for the entire flight are as follows:

	MEAN	STANDARD DEVIATION
Navigation computer crosstrack error	.02 nm	.25 nm
Navigation computer alongtrack error	-.13 nm	.09 nm

6.3.2.3 Flight Technical Error

Flight technical error, based on the deviation signal presented to the pilot, was evaluated for the fourteen segments flown during the test. The errors were very small in terms of deflection values ($\pm$ 5 dots is full scale). However, due to the low deflection sensitivity of $\pm$ 7.5 nm full scale (or 1.5 nm per dot) for the unit that was tested, the flight technical error values appear fairly large in terms of nautical miles. For the entire route the statistical values were found to be:

	MEAN	STANDARD DEVIATION
Omega/VLF Flight Technical Error	-.01 nm (-.007 dots)	.34 nm (.226 dots)

For helicopters and other slower speed aircraft, the course deviation sensitivity used in this project could be increased by a factor of two or three without seriously affecting the flyability of the deviation needle. The increased sensitivity would make the deviations more responsive to aircraft heading changes but the overall effect on system accuracy would be negligable because other error sources are much larger than flight technical error values.

6.4 OVERALL SYSTEM PERFORMANCE

Total system alongtrack and crosstrack error plots for the fourteen flight segments are shown in Appendix B. The alongtrack plots have the same resolution and unfiltered appearance as the DRMS error plots shown in Section 6.3.2.1. This appearance is due to the limited resolution of the distance to waypoint information and the lack of position filtering due to the long repetition period of the Omega signal format.

The crosstrack data shown in Appendix B exhibit a smooth but oscillatory behavior. Since the crosstrack error represents the actual position of the aircraft with respect to desired track, the smooth character of the data is expected. The oscillatory nature of the signal appears to have a period of approximately twenty minutes. This characteristic of the data is believed to be a result of filtering the crosstrack deviation by the receiver/processor to produce a smooth deviation signal for the pilot or autopilot.

A comparison of the accuracy obtained during the flight segments with enroute accuracy standards contained in FAA Advisory Circular 90-45A for non-VOR/DME area navigation systems is presented in Table 6.2. For ten of the fourteen flight segments, both alongtrack and crosstrack errors were within AC 90-45A criteria. On Segment 4 the crosstrack errors were slightly in excess of the FAA standard, and on Segment 1 a degradation in accuracy occured in northern Florida which produced several crosstrack error values which were in excess of AC 90-45A limits. This problem was discussed in Section 6.3.2.1.

The most obvious accuracy problems occurred on Segments 6 and 12. Segment 6 was the night flight between Bismarck, ND and St. Paul, MN. The difficulties concerning station availability and fix geometry on this segment are discussed in detail in Section 6.3.2.1. On Segment 12 a bias error of about -2.0 nm is apparent throughout the flight segment (see Figure B.12 in Appendix B). This consistent offset causes most of the data points on this segment to exceed the FAA standards. The specific cause of this error could not be determined with certainty.

The accuracy problems observed on Segments 6 and 12 caused the overall error values to exceed AC 90-45A standards. The alongtrack values are 8.9 percentage points less than the 95% criteria and the

crosstrack values are 1.6 percentage points below the criteria. The distribution of alongtrack and crosstrack errors, summarized for the entire flight, are presented in Figure 6.29 and 6.30. These histograms exhibit the typical bell shaped form associated with the normal or Gaussian distribution. Also apparent are the tails of the distribution which extend beyond the AC 90-45A limits.

A summary of the statistical errors in terms of the mean, standard deviation, and the mean plus/minus two standard deviations are presented in Table 6.3. Also shown in Table 6.3 are the area navigation accuracy requirements in AC 90-45A . It can be observed that the Omega/VLF crosstrack accuracy observed during the test nearly meets the AC 90-45A criteria. However, the alongtrack errors exceed the requirement by about 0.9 nm .

Table 6.2 Percentage of Data Points within AC 90-45A Accuracy Limits by Flight Segment

SEGMENT NUMBER	ORIGIN	DESTINATION	Percentage of Data Points within ±1.5 nm Alongtrack	Percentage of Data Points within ±2.5 nm Crosstrack
1	Palm Beach, FL	Columbia, SC	99.6%	72.5%
2	Columbia, SC	Wilmington, DE	100.0%	100.0%
3	Wilmington, DE	Flint, MI	99.6%	100.0%
4	Flint, MI	St. Paul, MN	99.3%	93.5%
5	St. Paul, MN	Bismarck, ND	100.0%	100.0%
6	Bismarck, ND	St. Paul, MN	33.0%	31.2%
7	St. Paul, MN	Dickinson, ND	99.4%	98.9%
8	Dickinson, ND	Missoula, MT	99.7%	100.0%
9	Missoula, MT	Eugene, OR	100.0%	100.0%
10	Eugene, OR	Fresno, CA	99.4%	100.0%
11	Fresno, CA	Albuquerque, NM	100.0%	100.0%
12	Albuquerque, NM	Little Rock, AR	8.5%	100.0%
13	Little Rock, AR	Montgomery, AL	100.0%	100.0%
14	Montgomery, AL	Palm Beach, FL	100.0%	100.0%
TOTAL			86.1%	93.4%

Segments in which less than 95% of data points meet AC 90-45A Accuracy criteria

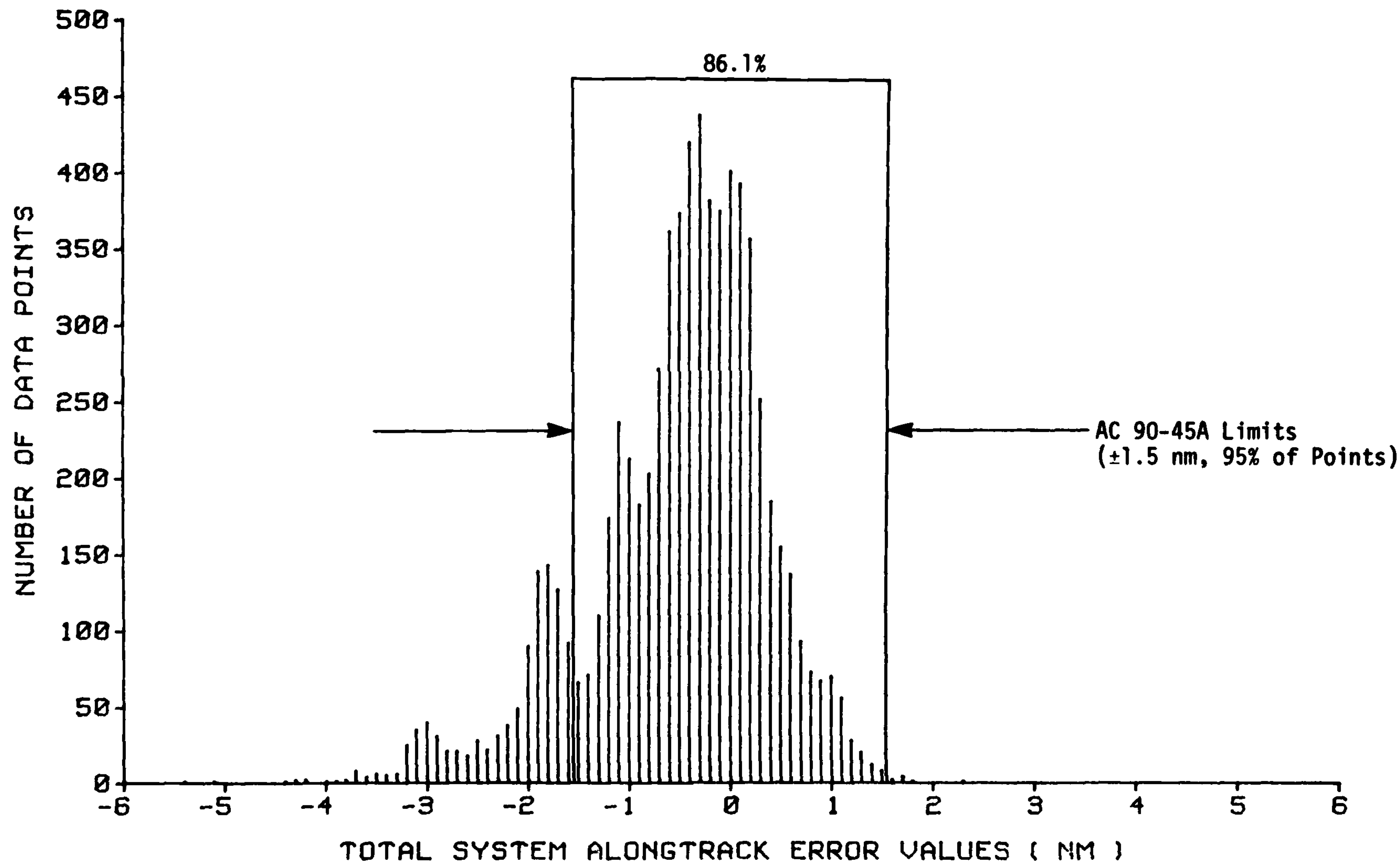


Figure 6.29 Histogram of Alongtrack Error

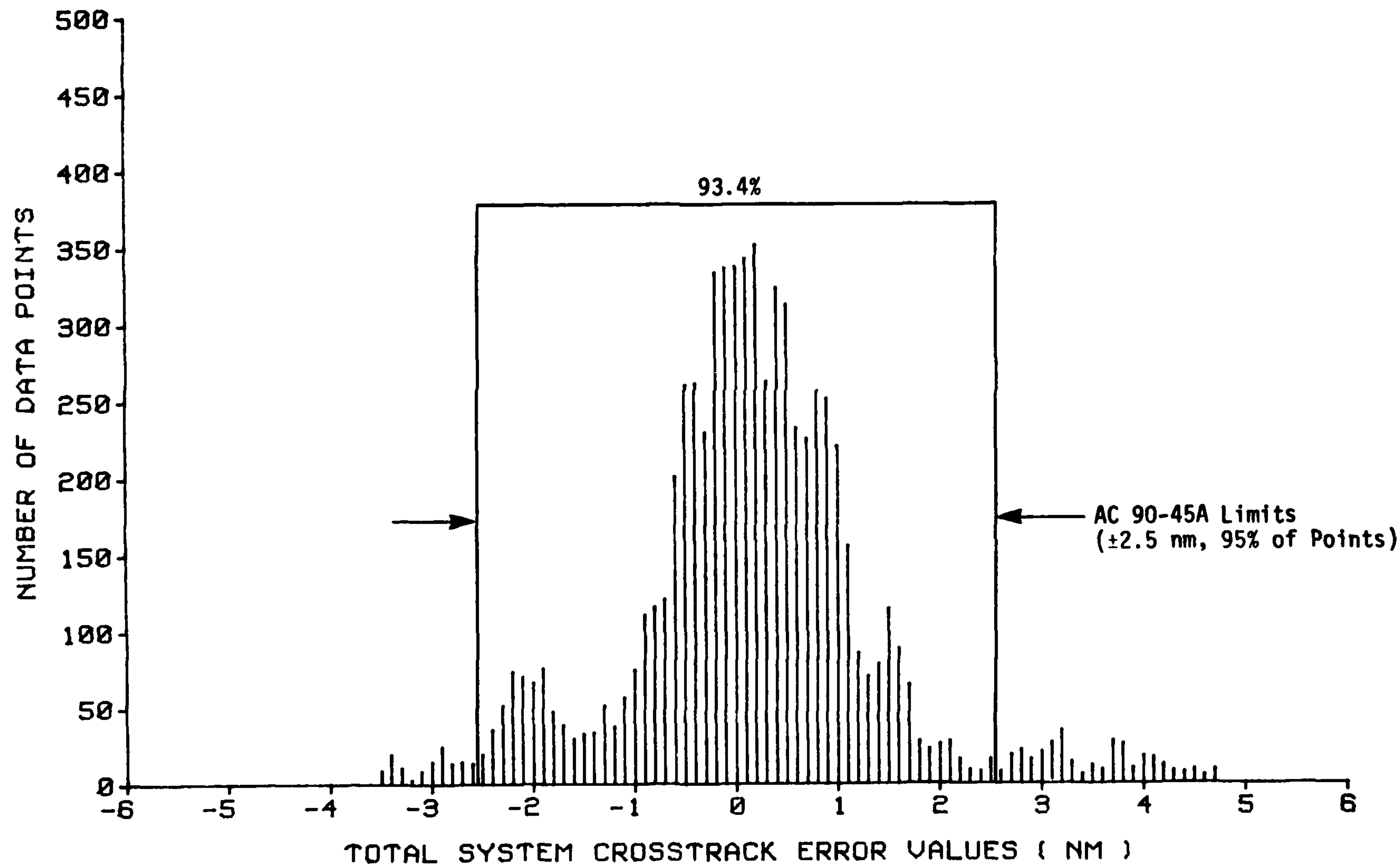


Figure 6.30 Histogram of Crosstrack Error

Table 6.3 Omega/VLF Accuracy Summary
(nautical miles)

Error Quantity	Mean ($\bar{x}$)	Standard Deviation (σ)	$\bar{x} - 2\sigma$	$\bar{x} + 2\sigma$	AC 90-45A Requirements	$\bar{x}-2\sigma$ Δ	$\bar{x}+2\sigma$ Δ
Northing Error	0.06	0.91	-1.76	1.88			
Easting Error	0.50	1.20	-1.90	2.90			
DRMS	1.24	1.00					
Total System Crosstrack	0.17	1.25	-2.33	2.67	$\pm$2.50	+.17	-.17
Total System Alongtrack	-0.63	0.89	-2.41	1.15	$\pm$1.50	-.91	+.35
Navigation System Crosstrack	0.16	1.25	02.34	2.66			
Navigation System Alongtrack	-0.39	0.90	-2.19	1.41			
Navigation Computer Crosstrack	0.02	0.25	-0.48	0.52			
Navigation Computer Alongtrack	-0.24	0.15	-0.54	0.06			
Flight Technical Error	-0.01	0.34	-0.69	0.67			

/NOTE/ Based on 7254 Data Points

The overall performance of the Omega/VLF system was quite good, but there were two problem areas that are of some concern. These are:

- large errors and marginal signal coverage in the north central states (Minnesota, North & South Dakota) within the area where North Dakota is unusable. This problem also affects south central Canada (southern Manitoba, southeastern Saskatchewan and southwestern Ontario).
- failure of the system to resume navigation after loss of synchronization on two occasions.

7.0 CONCLUSIONS

The following conclusions were developed from the flight test of the ARINC 599 Omega/VLF system in CONUS:

- Total system alongtrack and crosstrack errors measured during the test were worse than the enroute standards contained in the Federal Aviation Administration Advisory Circular 90-45A for non-VOR/DME systems by 0.9 nm alongtrack and 0.2 nm crosstrack.

- The major source of Omega/VLF system error is the error in deriving aircraft position from the Omega and VLF phase measurements and signal propagation models.

- Flight technical errors of 0.7 nm (2σ) were measured during the test.

- Computational errors of 0.5 nm (2σ) in crosstrack were measured in the test. In alongtrack the computational error had a mean value of -0.24 nm with a 0.3 nm variation (2σ) about the mean value. The primary source of computation error appears to be derived from smoothing of the navigation data for presentation to the pilot.

- The largest system errors and the poorest signal coverage observed during the test was at night in the North Central states in the area where the North Dakota Omega station is deselected. Deselection occurred when the aircraft was within 300 nm of the station. This problem affects flights in Minnesota, North Dakota, South Dakota, southern Manitoba, southeastern Saskatchewan and southwestern Ontario. These large errors are due to station geometry of available signals.

- The system lost synchronization on two occasions, once for twelve (12) minutes near Flint, Michigan prior to landing and once near Fargo, North Dakota for a period of two (2) hours and thirty-nine (39) minutes. In both instances the system did not resynchronize nor did it resume valid navigation prior to landing. In both instances when synchronization was lost, the warning flag was in view on the pilot's course deviation indicator showing that the navigation information was unreliable. The cause of the loss of synchronization could not be determined.

- The flat plate E-field antenna worked well during the test. On several occasions rain and snow conditions were encountered, but there were no apparent signal loss situations caused by precipitation static with the E-field antenna.

- The flight crew found the control display unit to be functionally well organized and the system, in general, to be easy to use. The pilots liked the automatic waypoint advance feature of the system and they used it throughout the test.

- The flight crew indicated that a more sensitive course deviation indication could be utilized for aircraft such as helicopters and general aviation aircraft which operate at speeds of 100 to 200 knots.

REFERENCES

1. Anonymous, "Advisory Circular 90-45A" Department of Transportation, Federal Aviation Administration, February 21, 1975.

2. Selby, Samuel M., <u>Standard Mathematical Tables</u>, Twenty-First Edition, The Chemical Rubber Company, Cleveland, Ohio 44128.

APPENDIX A

DATA PROCESSING ALGORITHMS

This Appendix contains data processing equations that were used to 1) determine the aircraft position from DME measurements, and 2) compute system accuracy parameters. The equations for the minimum mean squared DME residual error and the DRMS position error estimate are developed in the appendix. Equations for great circle distance and bearing over a spherical earth are also included in the section. These equations were obtained from navigational texts.

A.1 MINIMIZATION OF THE MEAN SQUARED RESIDUAL ERROR

Figure A.1 presents the geometric configuration of the residual error problem. Assume that the current estimate of the aircraft's position is at P_1. Also assume that after correction the estimated position of the aircraft is at P_2. The position P_2 is east of P_1 by an amount ΔE and north of P_1 by an amount of ΔN. The computed distance from the current position is D_c and the measured distance from the DME is D_m. The DME error is then expressed as

$$\Delta D_i = D_m - D_c = \Delta E \sin \beta_i + \Delta N \cos \beta_i + \text{Residual}_i$$

where β_i is the azimuth from the i th DME station to the estimated aircraft position P_1 as measured at P_1, and Residual_i is any remaining error after the shift from P_1 to P_2 is made.

Solving for Residual_i

$$\text{Residual}_i = R_i = \Delta D_i - \Delta E \sin \beta_i - \Delta N \cos \beta_i$$

and squaring

$$\begin{aligned} R_i^2 = {} & \Delta D_i^2 + \Delta E^2 \sin^2 \beta_i + \Delta N^2 \cos^2 \beta_i \\ & - 2\,\Delta D_i\,\Delta E \sin \beta_i - 2\Delta D_i\,\Delta N \cos \beta_i \\ & + 2\,\Delta E\,\Delta N \sin \beta_i \cos \beta_i \end{aligned}$$

The mean value of the squared residual errors is

$$\begin{aligned} \Sigma R_i^2 = {} & \Sigma \Delta D_i^2 + \Delta E^2\,\Sigma \sin \beta_i^2 + \Delta N^2\,\Sigma \cos^2 \beta_i \\ & - 2\Delta E\,\Sigma \Delta D_i \sin \beta_i - 2\Delta N \Sigma \Delta D_i \cos \beta_i \\ & + 2\,\Delta E\,\Delta N\,\Sigma \sin \beta_i \cos \beta_i \end{aligned}$$

where Σ represents the summation over the number of available DME stations.

The minimumization is performed by extracting the partial derivatives of the mean squared residual error with respect to the unknowns ΔE and ΔN and setting these derivatives to zero.

$$\frac{\partial \Sigma R_i^2}{\partial E} = 0 = 2\,\Delta E\,\Sigma \sin \beta_i^2 - 2\,\Sigma \Delta D_i \sin \beta_i + 2\,\Delta N\,\Delta \sin \beta_i \cos \beta_i$$

$$\frac{\partial \Sigma R_i}{\partial N} = 0 = 2\,\Delta N\,\Sigma \cos^2 \beta_i - 2\,\Sigma \Delta D_i \cos \beta_i + 2\,\Delta E\,\Sigma \sin \beta_i \cos \beta_i$$

Collecting terms

$$\begin{bmatrix} \Sigma \Delta D_i \sin \beta_i \\ \Sigma \Delta D_i \cos \beta_i \end{bmatrix} = \left[\begin{array}{c:c} \Sigma \sin^2 \beta_i & \Sigma \sin \beta_i \cos \beta_i \\ \Sigma \sin \beta_i \cos \beta_i & \Sigma \cos^2 \beta_i \end{array}\right] \begin{bmatrix} \Delta E \\ \Delta N \end{bmatrix} \quad \text{(Equation A.1)}$$

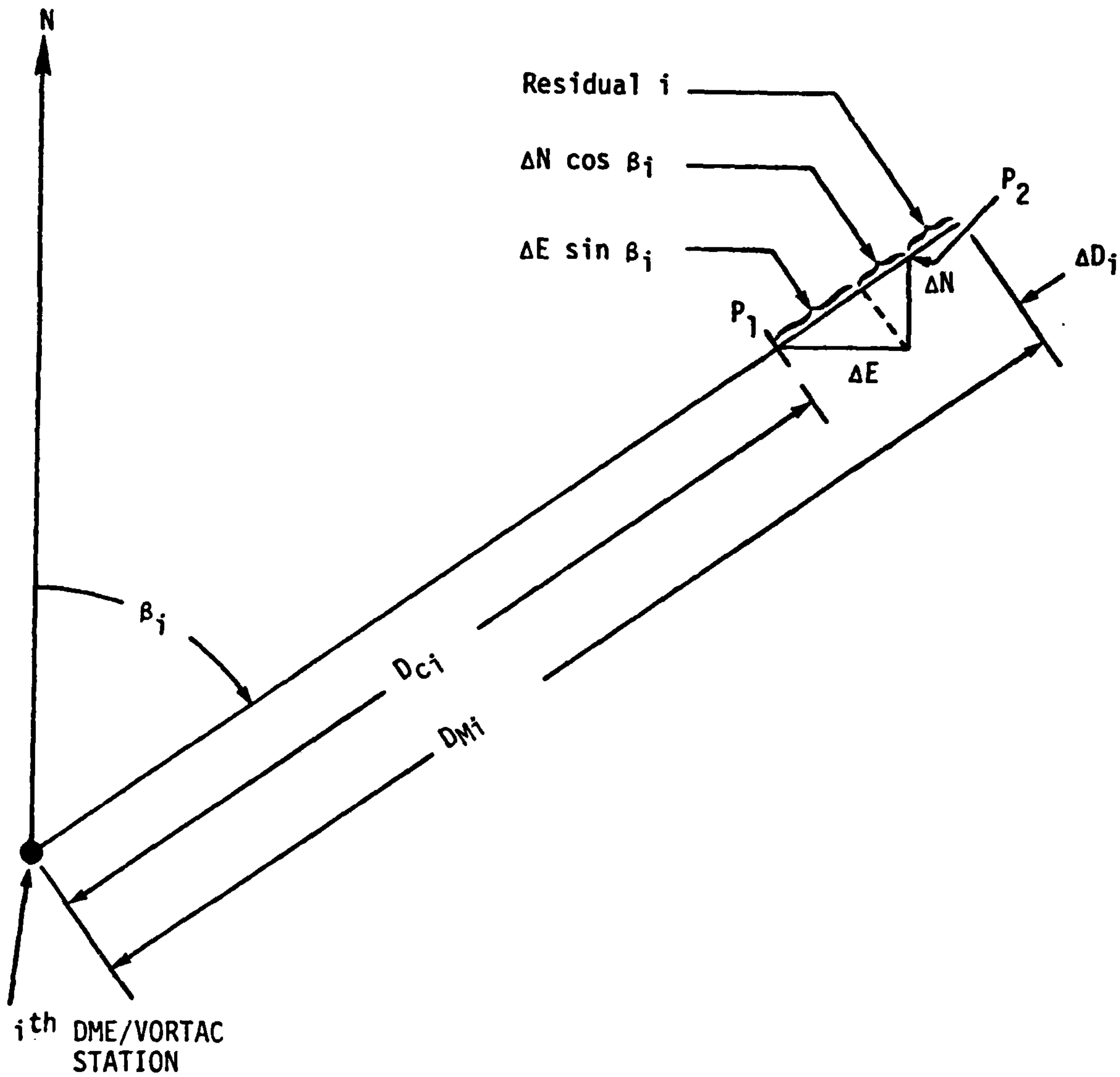


Figure A.1 Residual Error Geometry

Solving for ΔE and ΔN

$$\Delta E = \frac{(\Sigma\Delta D_i \sin \beta_i)(\Sigma\cos^2 \beta_i) - (\Delta\Sigma D_i \cos \beta_i)(\Sigma\sin \beta_i \cos \beta_i)}{(\Sigma\cos^2 \beta_i)(\Sigma\sin^2 \beta_i) - (\Sigma \sin \beta_i \cos \beta_i)^2}$$

$$\Delta N = \frac{(\Sigma D_i \cos \beta_i)(\Sigma \sin^2 \beta_i) - (\Sigma\Delta D_i \sin \beta_i)(\Sigma \sin \beta_i \cos \beta_i)}{(\Sigma\cos^2 \beta_i)(\Sigma \sin^2 \beta_i) - (\Sigma \sin \beta_i \cos \beta_i)^2}$$

A.2 EVALUATION OF THE ROOT MEAN SQUARE POSITION ERROR (D_{RMS})

Equation A.1 can be utilized to develop the root mean square position error value which is the familiar D_{RMS} statistic. Expressed in matrix form Equation A.1 can be written

$$[\Delta D] = [A]\,[\Delta P]$$

where $[\Delta D] = \begin{bmatrix} \Sigma\Delta D_i \sin \beta_i \\ \Sigma\Delta D_i \cos \beta_i \end{bmatrix}$ a 2x1 matrix

$[A] = \left[\begin{array}{c:c} \Sigma\sin^2\beta_i & \Sigma\sin \beta_i \cos \beta_i \\ \Sigma\sin \beta_i \Sigma\cos \beta_i & \Sigma\cos^2 \beta_i \end{array}\right]$ a 2x2 matrix

$[\Delta P] = \begin{bmatrix} \Delta E \\ \Delta N \end{bmatrix}$ a 2x1 matrix

The solution for $[\Delta P]$ can be written

$$[\Delta P] = [A^{-1}]\,[\Sigma D]$$

where $[A^{-1}]$ is the inverse of A

The covarience matrix can be evaluated by multiplying $[\Delta P]$ by its transpose, $[\Delta P]^T$, and averaging the result.

$$[\Delta P]^T = [A^{-1}]\,[\Delta D]^{\;T} = [\Delta D]^T [A^{-1}]^T = [\Delta D]^T [A^{-1}]$$

Since A is symmetrical $[A]^T = [A]$ and $[A^{-1}]^T = [A^{-1}]$.

$$[\mathrm{cov}\ \Delta P] = E\left\{[\Delta P]\,[\Delta P]^T\right\} = E\left\{[A^{-1}]\,[\Delta D]\,[\Delta D]\,[A^{-1}]\right\}$$

where $E\{\ \}$ represents averaging.

Examining the right most term, the quantities in the A matrix are deterministic and can be brought outside the averaging process. This term then becomes

$$[\mathrm{cov}\ \Delta P] = [A^{-1}]\left\{[\Delta D]\,[\Delta D]^T\right\}[A^{-1}]$$

Expanding the averaging term

$$E\left\{[\Delta D]\,[\Delta D]^T\right\} = \begin{bmatrix} E\left\{\Sigma\Delta D_i \sin \beta_i\, \Sigma\Delta D_j \sin \beta_j\right\} & E\left\{\Sigma\Delta D_i \sin \beta_i\, \Sigma\Delta D_j \cos \beta_i\right\} \\ E\left\{\Sigma\Delta D_i \cos \beta_i\, \Sigma\Delta D_j \sin \beta_j\right\} & E\left\{\Sigma\Delta D_i \cos \beta_i\, \Sigma\Delta D_j \cos \beta_j\right\} \end{bmatrix}$$

(Equation A.2)

The averaging process depends upon the statistical character of the random variables ΔD_i and ΔD_j which are the errors in the DME measurements. These errors are of two types, those associated with the station and those associated with the receiver. For this analysis it is assumed that station errors are much geater than receiver errors. Furthermore, it is assumed that the ensemble of station errors have zero mean error and a standard deviation of σ_D and the station errors are independant of each other, which implies that the correlation between stations, ρ_{ij} is zero for $i \neq j$. Under these assumptions, equation A.2 becomes

$$E\left\{[\Delta D]\,[\Delta\, D]^T\right\} = \sigma_D{}^2\begin{bmatrix}\Sigma\sin^2\beta_i & \Sigma\sin\,\beta_i\,\cos\,\beta_i\\ \Sigma\sin\,\beta_i\;\Sigma\cos\,\beta_i & \Sigma\cos^2\beta_i\end{bmatrix}$$

$$= \sigma_D{}^2[A]$$

The matrix on the right is the matrix [A]. Therefore, the convarience matrix becomes

$$[\text{cov}\,\Delta P] = \sigma_D{}^2[A^{-1}]\,[A]\,[A^{-1}] = \sigma_D{}^2[A^{-1}]$$

or expanding

$$\begin{bmatrix}\sigma_E{}^2 & \rho_{EN}\sigma_E\,\sigma_N\\ \rho_{EN}\,\sigma_E\,\sigma_N & \sigma_N{}^2\end{bmatrix} = \frac{\sigma_D{}^2\begin{bmatrix}\Sigma\cos^2\beta_i & -\Sigma\sin\,\beta_i\Sigma\cos\,\beta_i\\ -\Delta\sin\,\beta_i\,\cos\beta_i & \Sigma\sin^2\beta_i\end{bmatrix}}{\Sigma\sin^2\beta_i\;\;\Sigma\cos^2\,\beta_i-(\Sigma\,\sin\,\beta_i\,\cos\,\beta_i)^2}$$

The trace of the matrix on the left is recognized as the square of the D_{RMS} statistic. Therefore,

$$D^2{}_{RMS} = \frac{\sigma_D{}^2(\Sigma\cos^2\,\beta_i + \Sigma\sin^2\,\beta_i)}{\Sigma\sin^2\,\beta_i\;\Sigma\cos^2\,\beta i - (\Sigma\sin\,\beta_i\,\cos\,\beta_i)^2}$$

which, upon inspection, reduces to

$$D^2{}_{RMS} = \frac{M\,\sigma_D{}^2}{\sum_{i=1}^{M}\;\sum_{j=i+1}^{M}\sin^2\,(\beta_i - \beta_j)}$$

where M is the number of DME stations.

A.3 GREAT CIRCLE DISTANCE AND COURSE EQUATIONS

The following equations were used to compute great circle distance (D) and course (ϕ) from an origin at P_1 and a destination at P_2 over a spherically shaped earth:

$$D = 60 * \frac{180}{\pi} * \theta$$

$$\theta = 2\sin^{-1}\sqrt{\sin^2\frac{(\beta_1 - \beta_2)}{2} + \cos\beta_1 \cos\beta_2 \sin^2\frac{\Delta\lambda}{2}}$$

where θ is the central angle at the center of the earth β_1, β_2 are the latitude coordinates of P_1 and P_2 and $\Delta\lambda$ is the difference in longitude $(\lambda_2 - \lambda_1)$

$$\psi = \tan^{-1}\left(\frac{\sin A}{\cos A}\right)$$

where $\sin A = \dfrac{\cos\beta_2 \sin\Delta\lambda}{\sin\theta}$

$$\cos A = \frac{\sin\beta_2 - \sin\beta_1 \cos\theta}{\cos\beta_1 \sin\theta}$$

where ψ is the course at P_1.

The sign convention for ψ is shown in Figure A.2

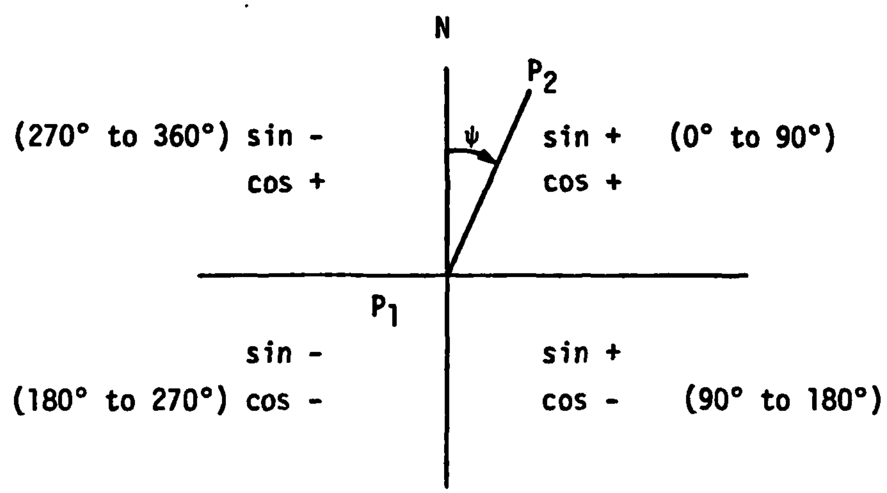


Figure A.2 Sign Convention for Course Computation

APPENDIX B

TOTAL SYSTEM ERROR PLOTS

Total system error data, recorded during times when Omega/VLF was utilized for navigation and the DME positioning system was operational are shown in Figure B.1 through B.28. Figures B.1 through B.14 present total system alongtrack errors (TSAT). Figures B.15 through B.28 present total system crosstrack errors (TSCT). Each plot contains data for one flight segment from takeoff to landing.

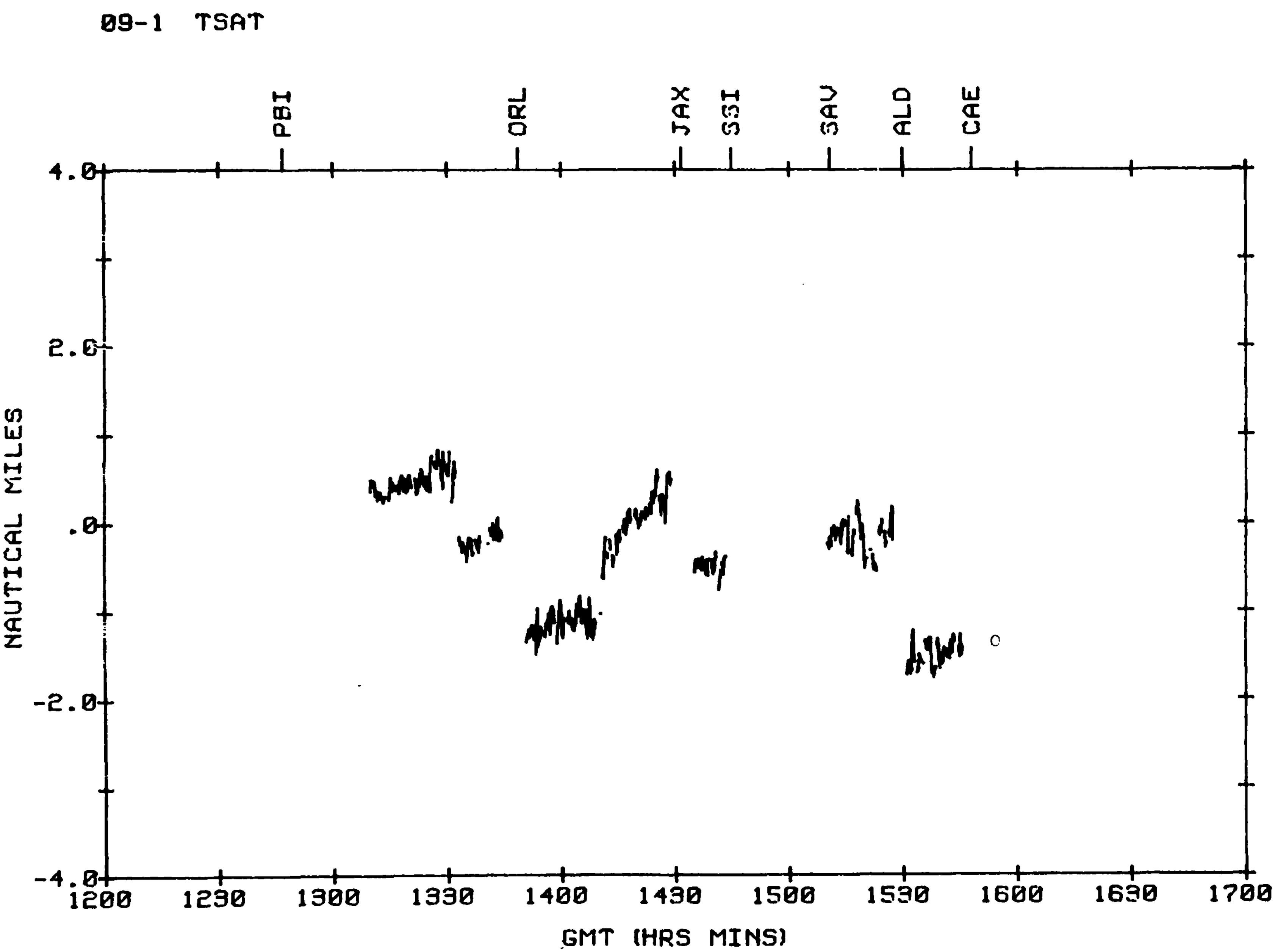


Figure B.1 Total System Alongtrack Error for Segment 1, Palm Beach, Fl to Columbia, SC (May 9, 1983)

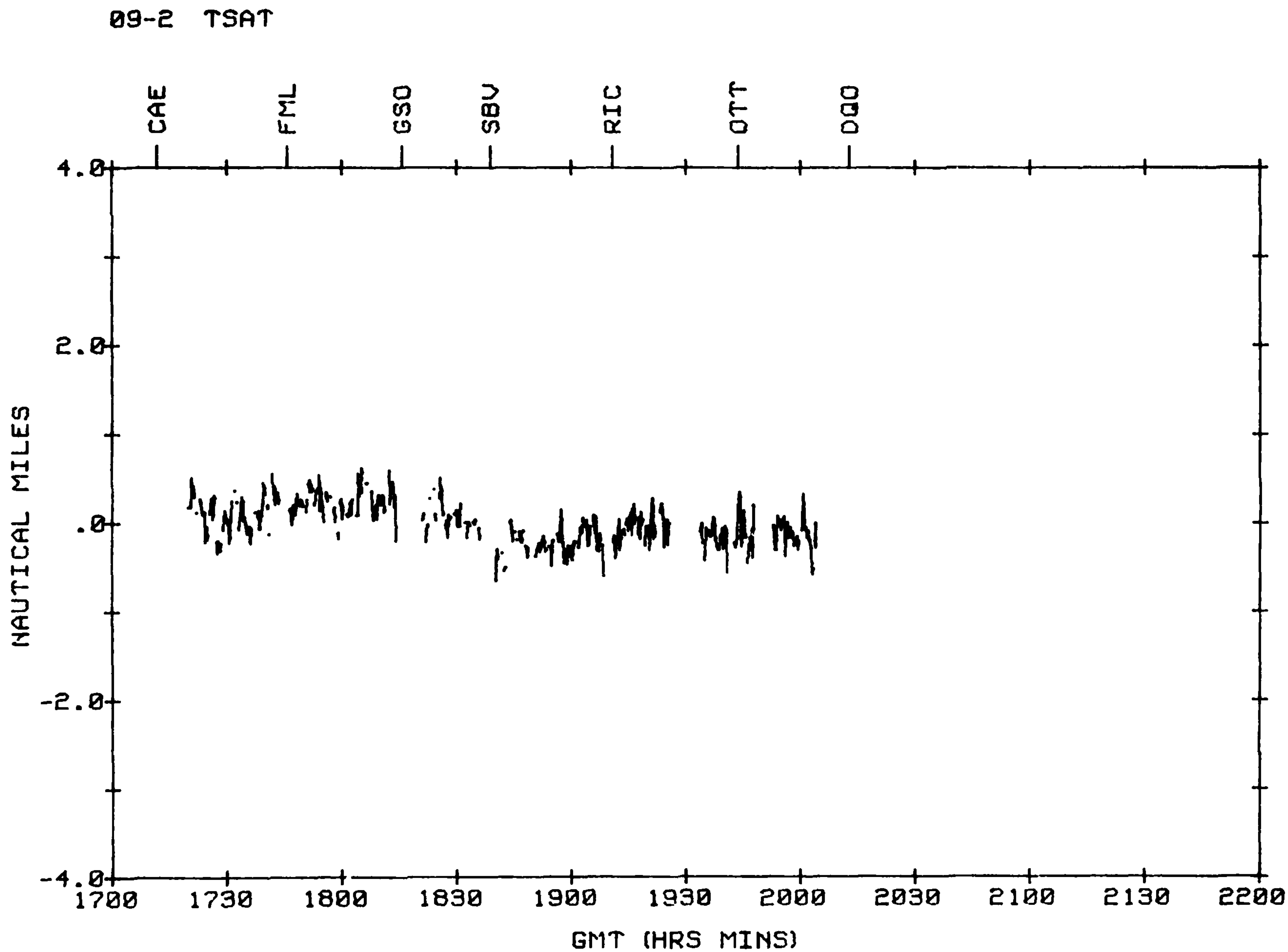


Figure B.2 Total System Alongtrack Error for Segment 2, Columbia, SC to Wilmington, DE (May 9, 1983)

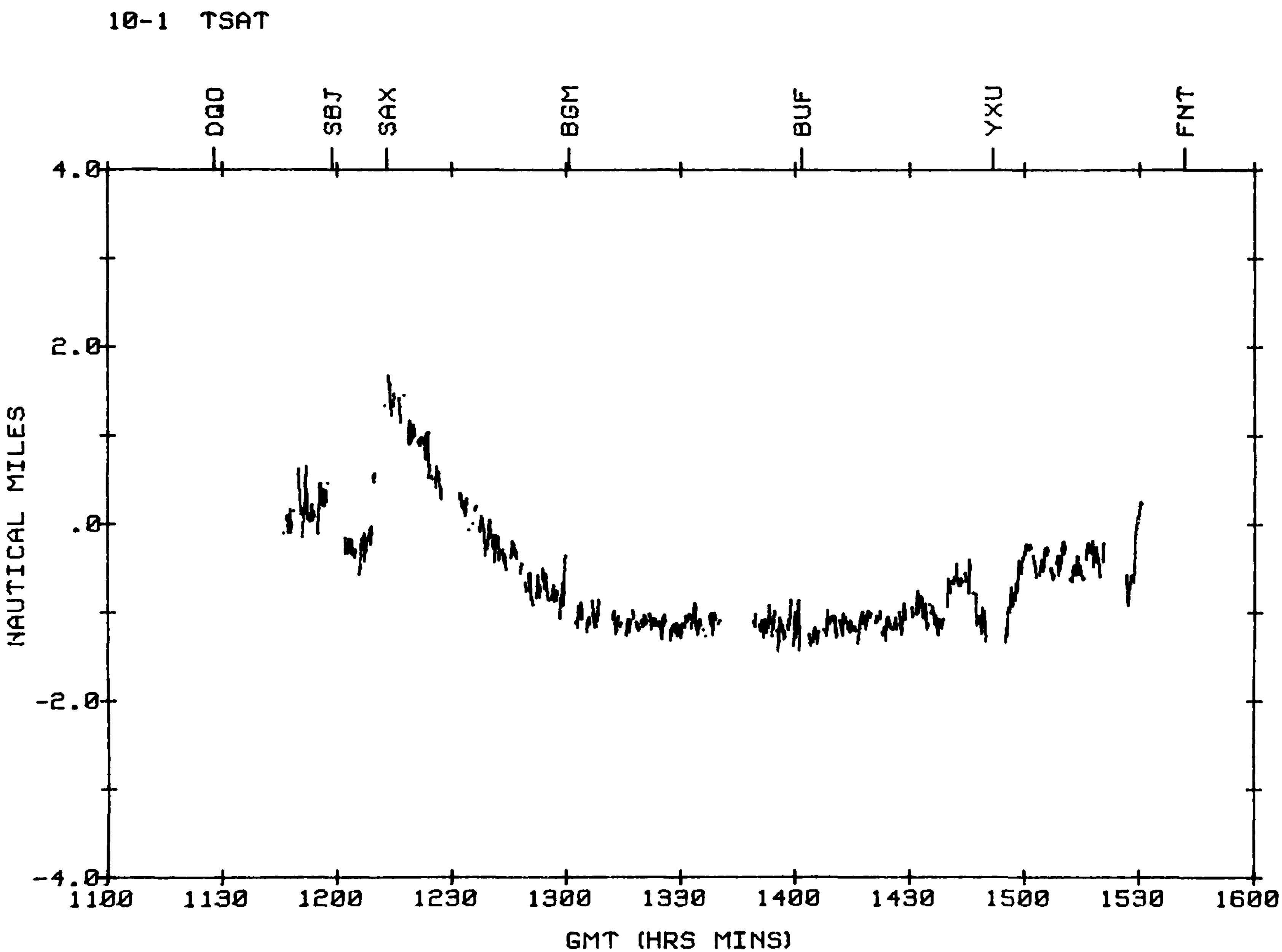


Figure B.3 Total System Alongtrack Error for Segment 3, Wilmington, DE to Flint, MI (May 10, 1983)

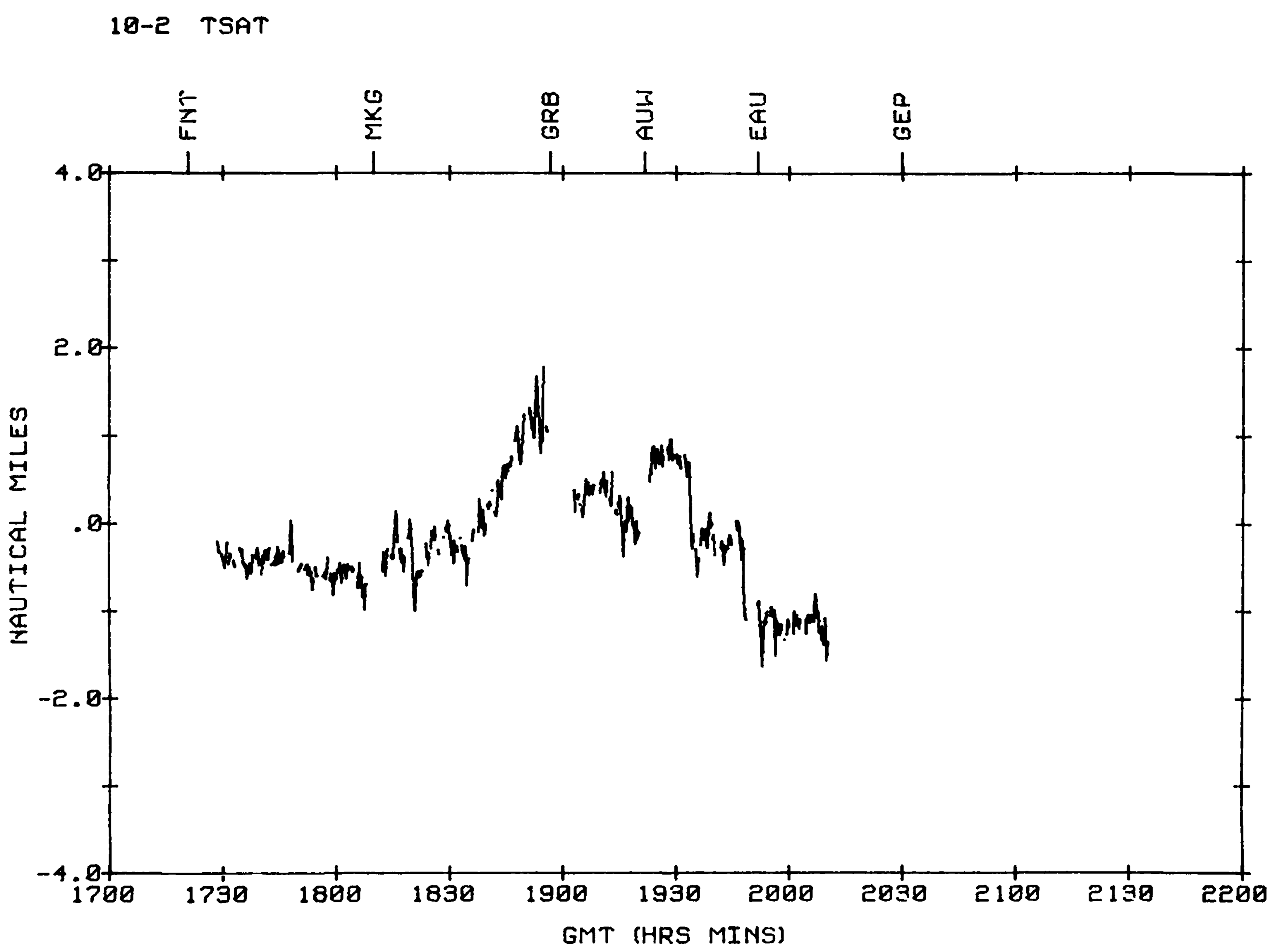


Figure B.4 Total System Alongtrack Error for Segment 4, Flint, MI to St. Paul, MN (May 10, 1983)

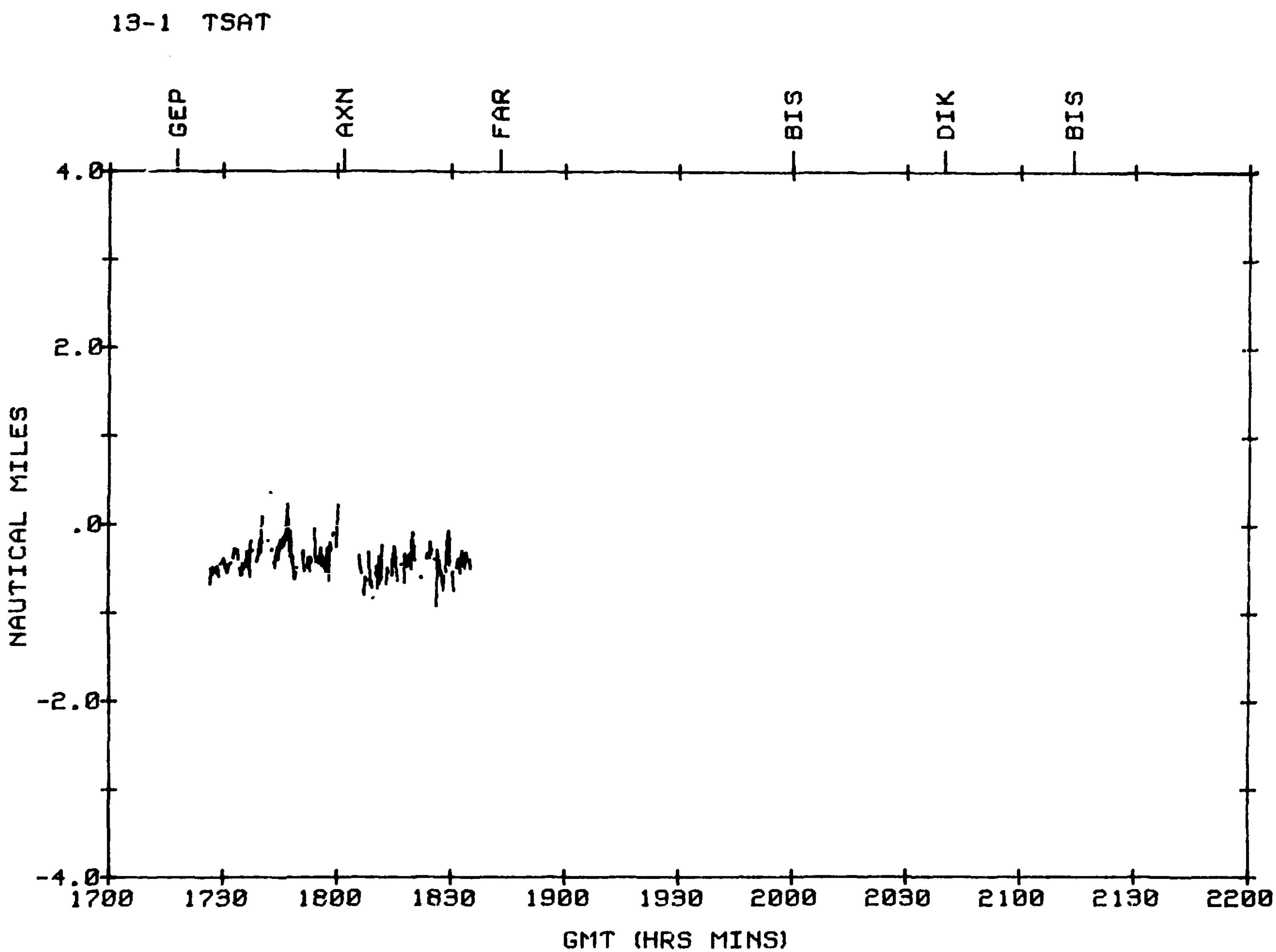


Figure B.5 Total System Alongtrack Error for Segment 5, St. Paul, MN to Bismarck, ND (May 13, 1983)

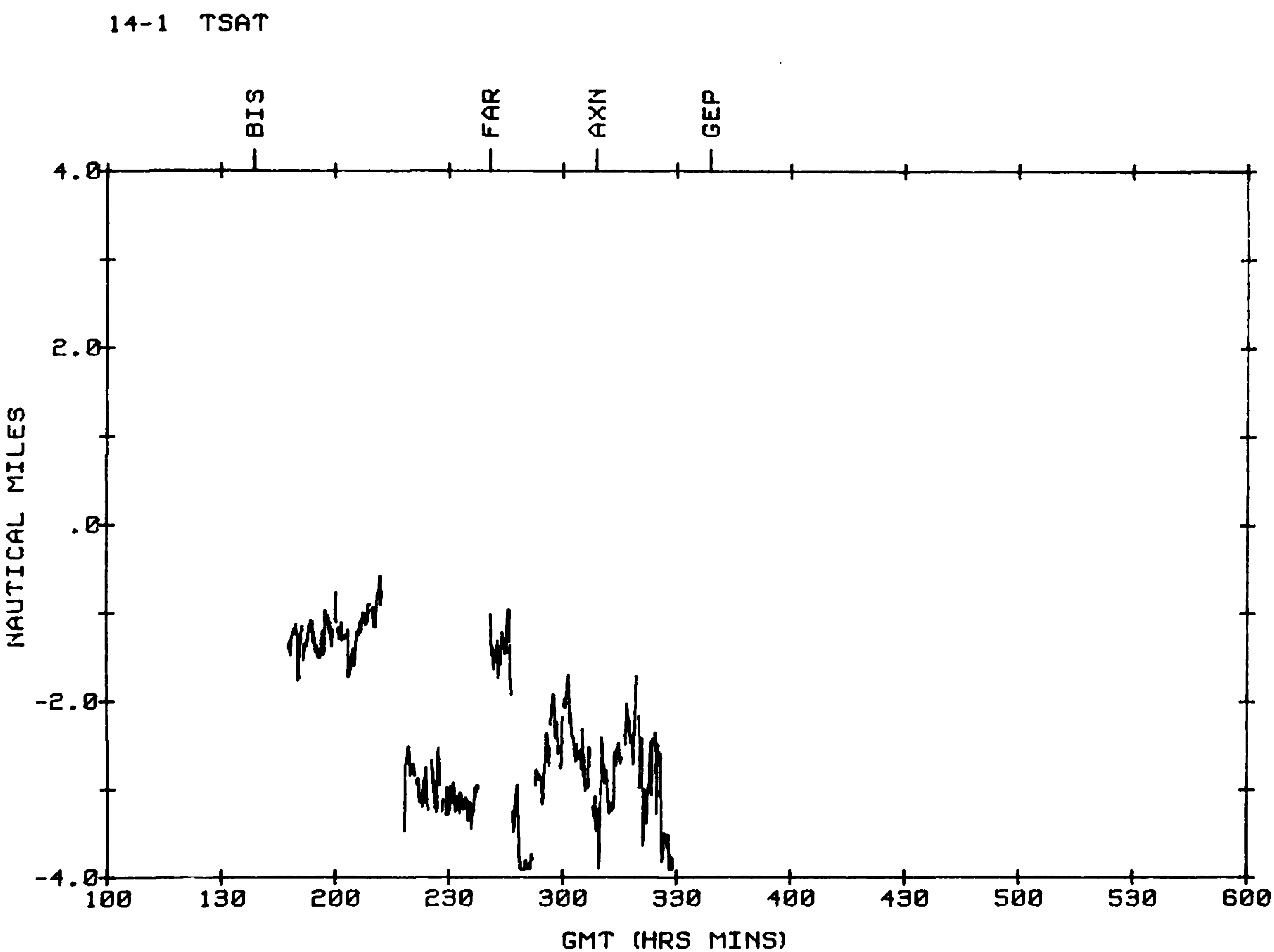


Figure B.6 Total System Alongtrack Error for Segment 6, Bismarck, ND to St. Paul, MN (May 14, 1983)

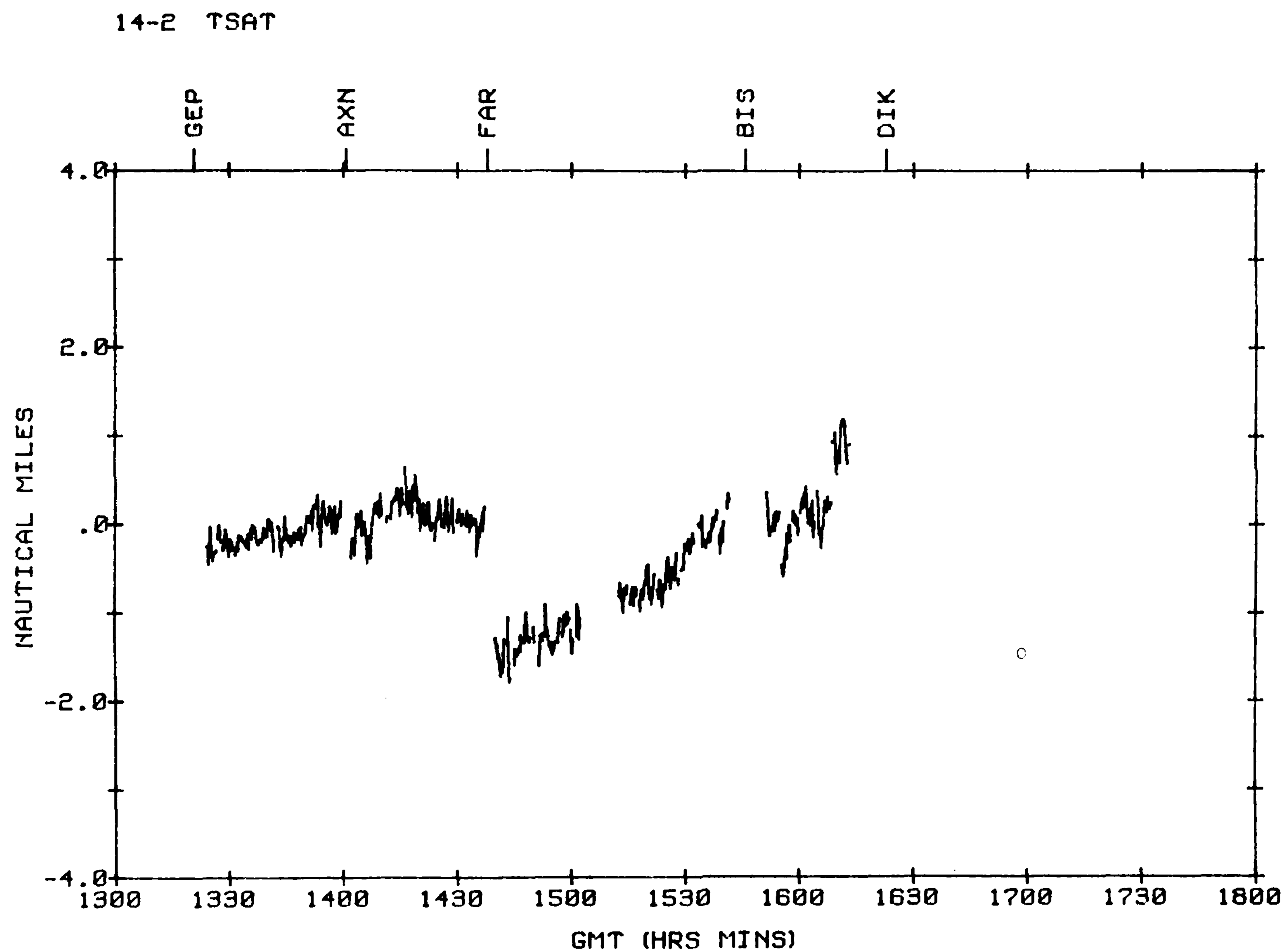
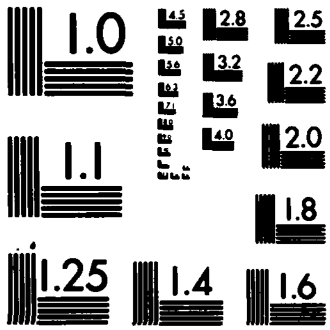


Figure B.7 Total System Alongtrack Error for Segment 7, St. Paul, MN to Dickinson, ND (May 4, 1983)

AD-A140 252 CONUS (CONTINENTAL UNITED STATES) OMEGA/VLF DATA 2/2
COLLECTION: FLIGHT TEST..(U) SYSTEMS CONTROL TECHNOLOGY
INC WEST PALM BEACH FL L D KING ET AL. DEC 83
UNCLASSIFIED DOT/FAA/PM-83/35 DOT-FA01-80-C-10080 F/G 17/7 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

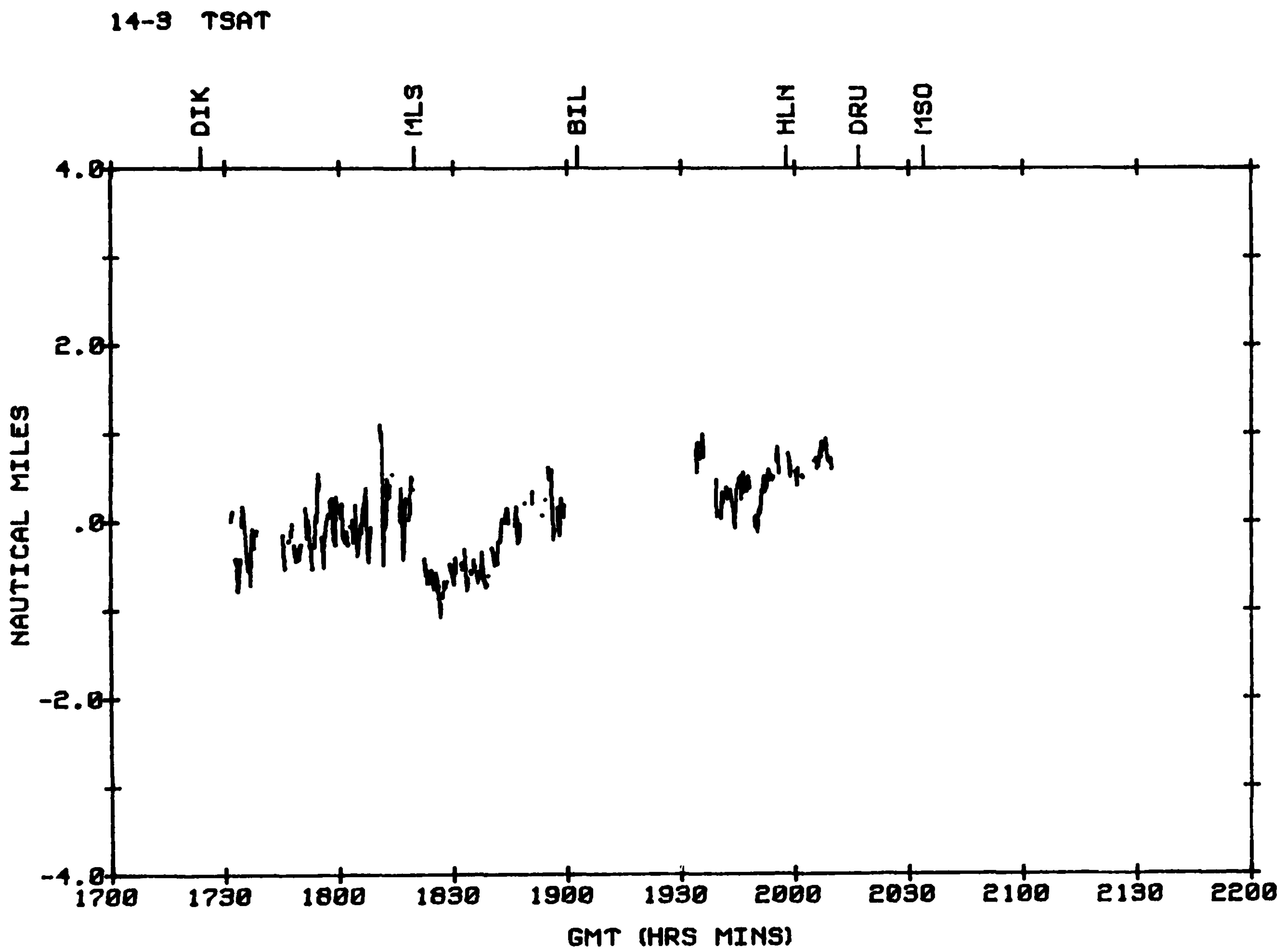


Figure B.8 Total System Alongtrack Error for Segment 8, Dickinson, ND to Missoula, MT (May 14, 1983)

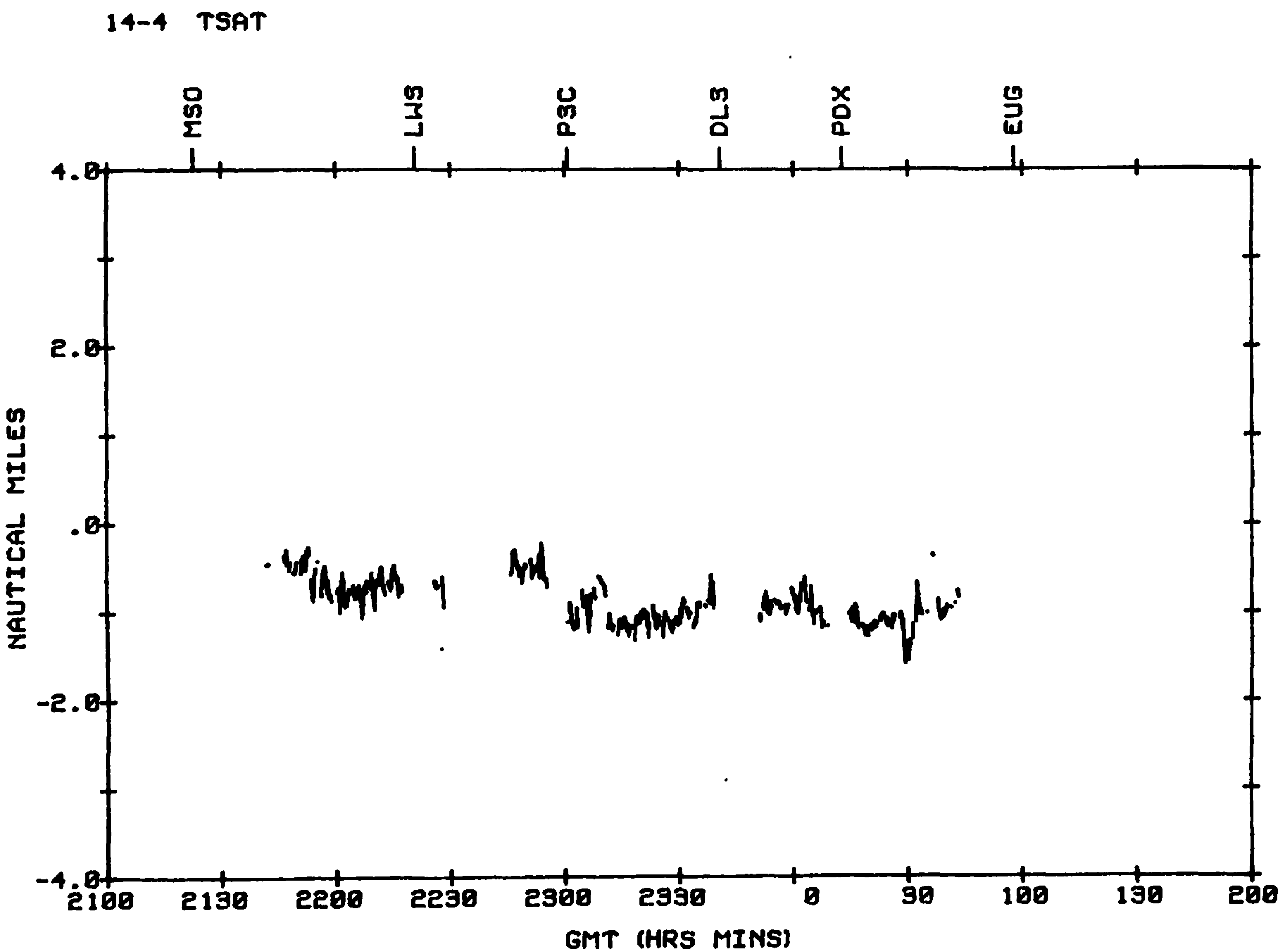


Figure B.9 Total System Alongtrack Error for Segment 9, Missoula, MT to Eugene, OR (May 14, 1983)

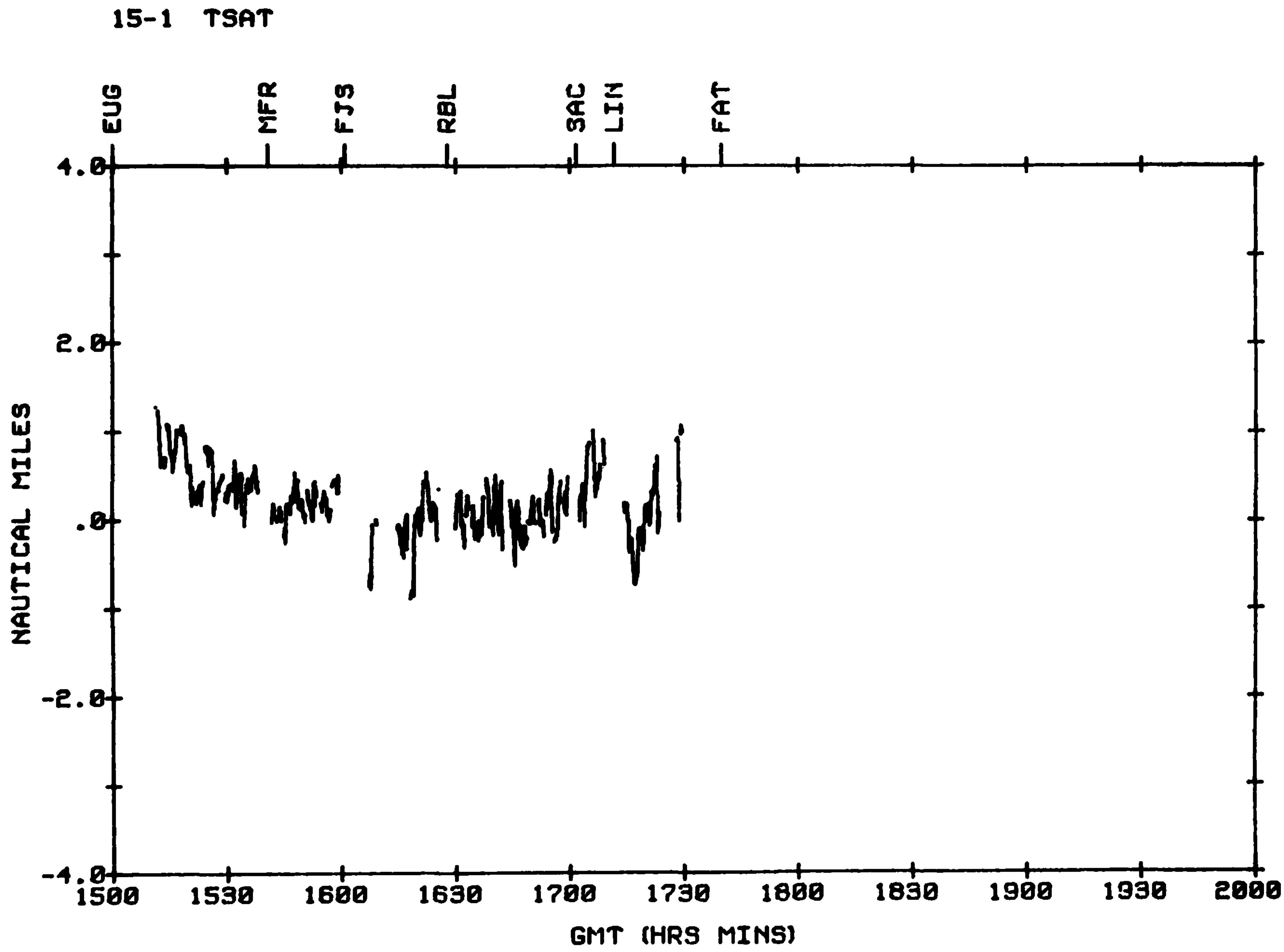


Figure B.10 Total System Alongtrack Error for Segment 10, Eugene, OR to Fresno, CA (May 15, 1983)

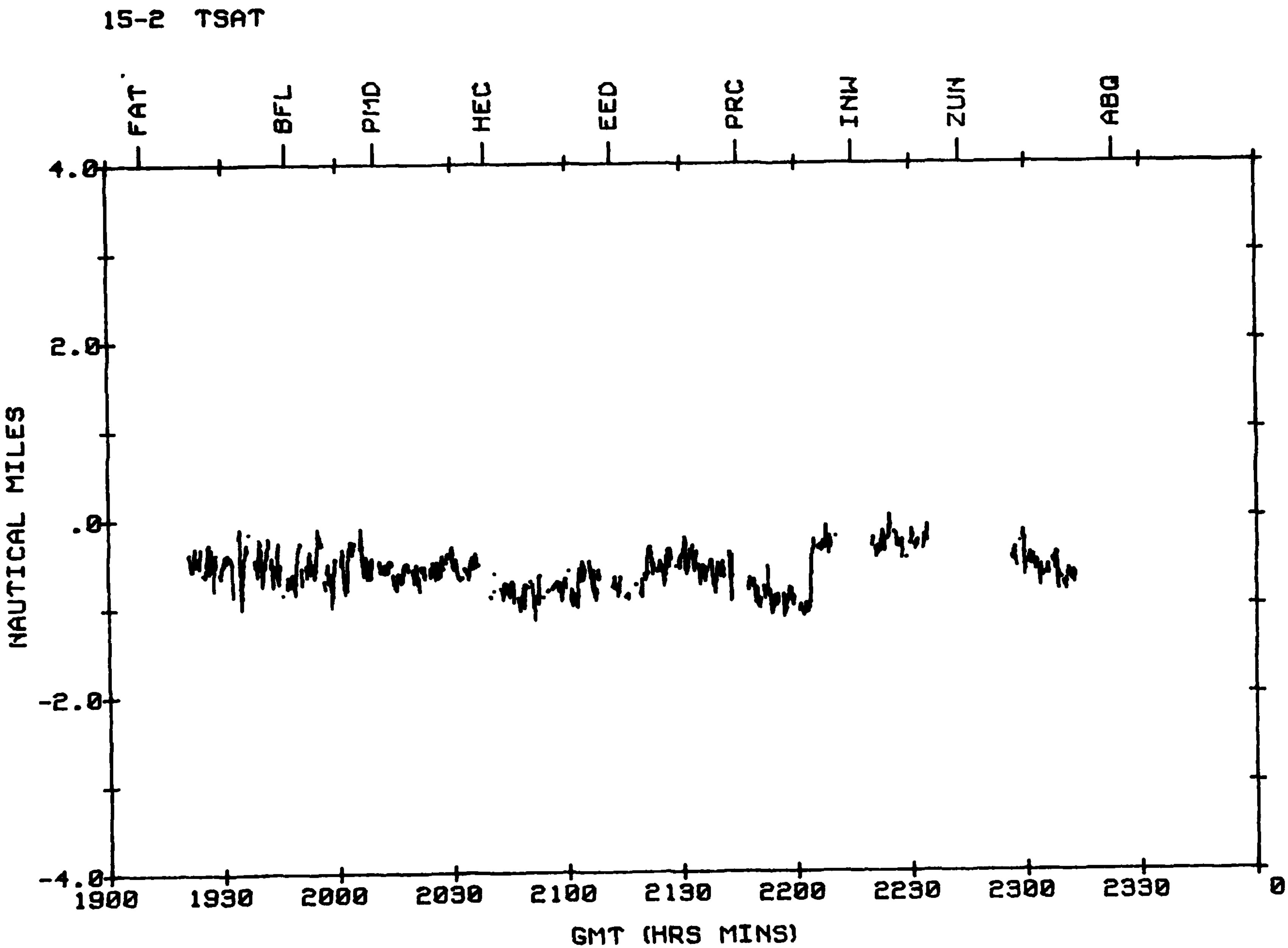


Figure B.11 Total System Alongtrack Error for Segment 11, Fresno, CA to Albuquerque, NM (May 15, 1983)

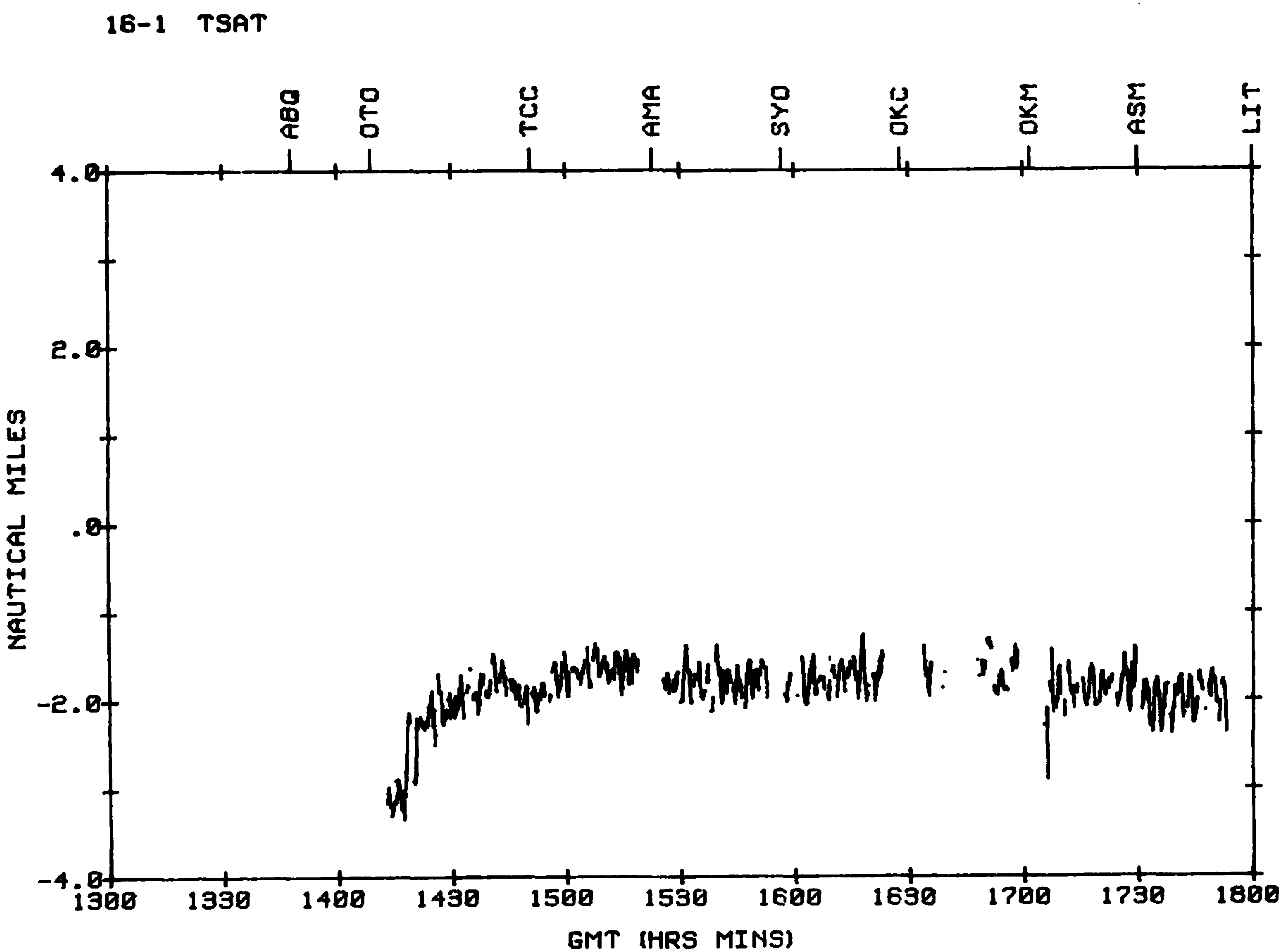


Figure B.12 Total System Alongtrack Error for Segment 12, Albuquerque, NM to Little Rock, AR (May 16, 1983)

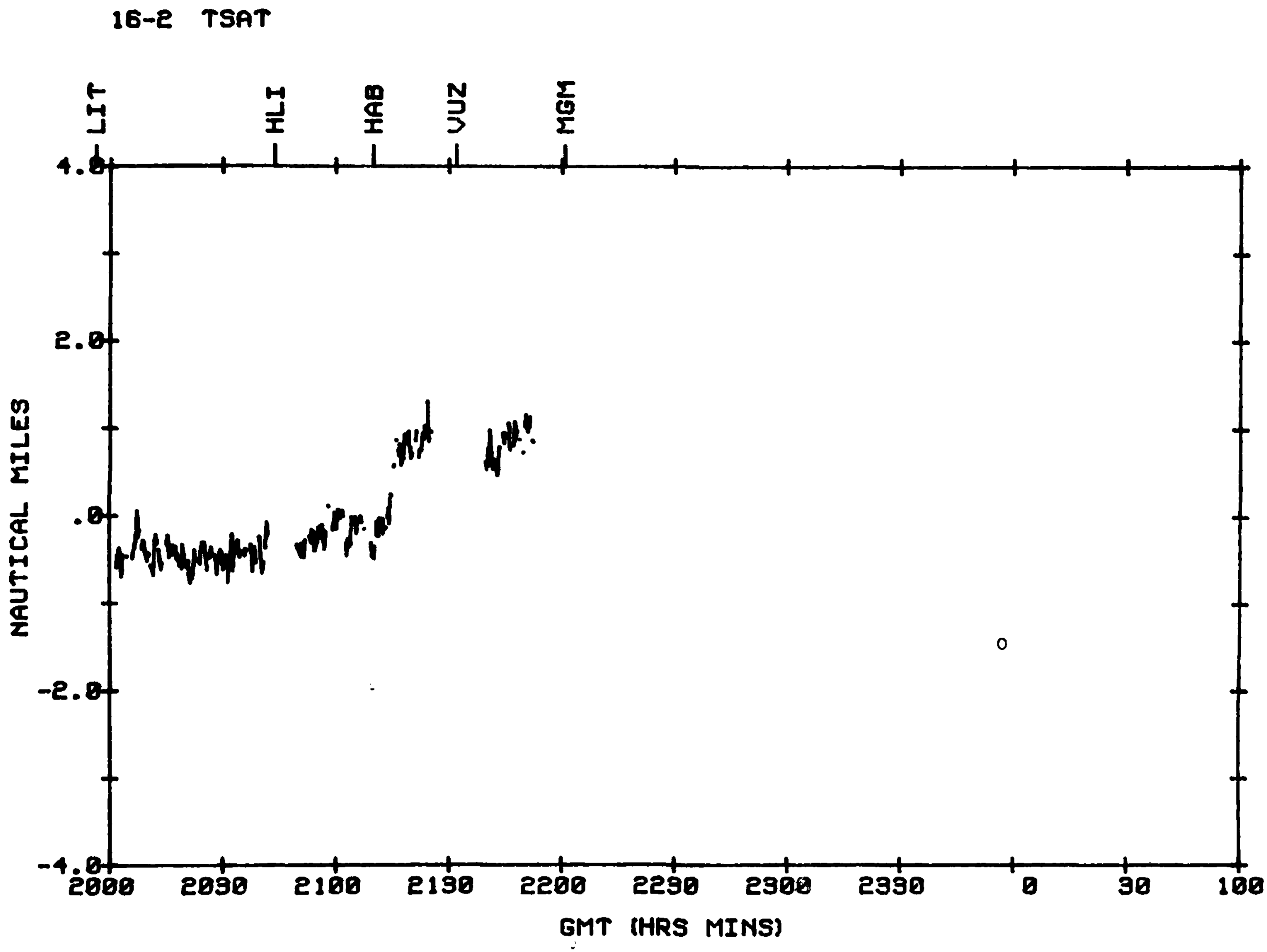


Figure B.13 Total System Alongtrack Error for Segment 13, Little Rock, AR to Montgomery, AL (May 16, 1983)

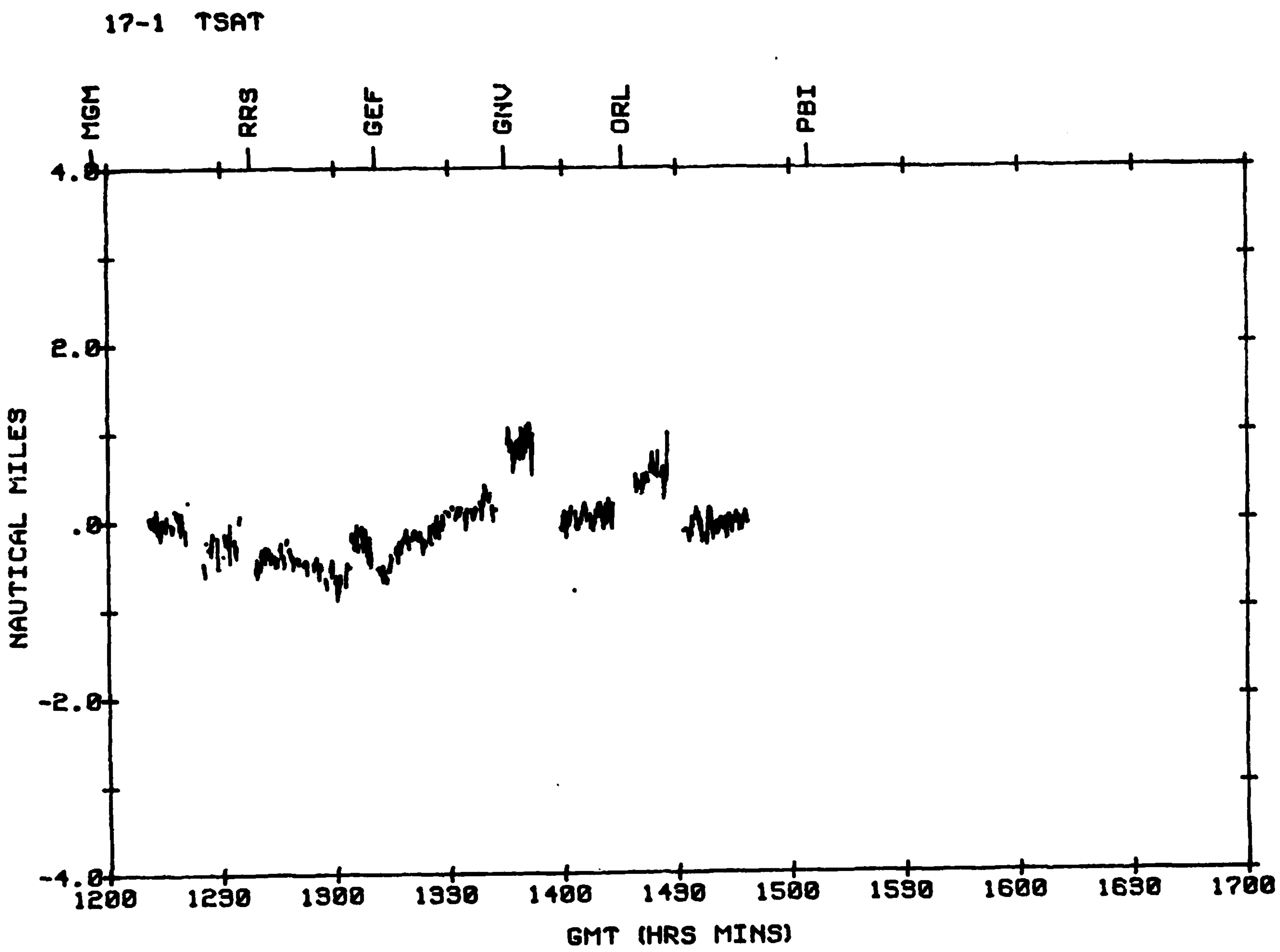


Figure B.14 Total System Alongtrack Error for Segment 14, Montgomery, AL to Palm Beach, FL (May 17, 1983)

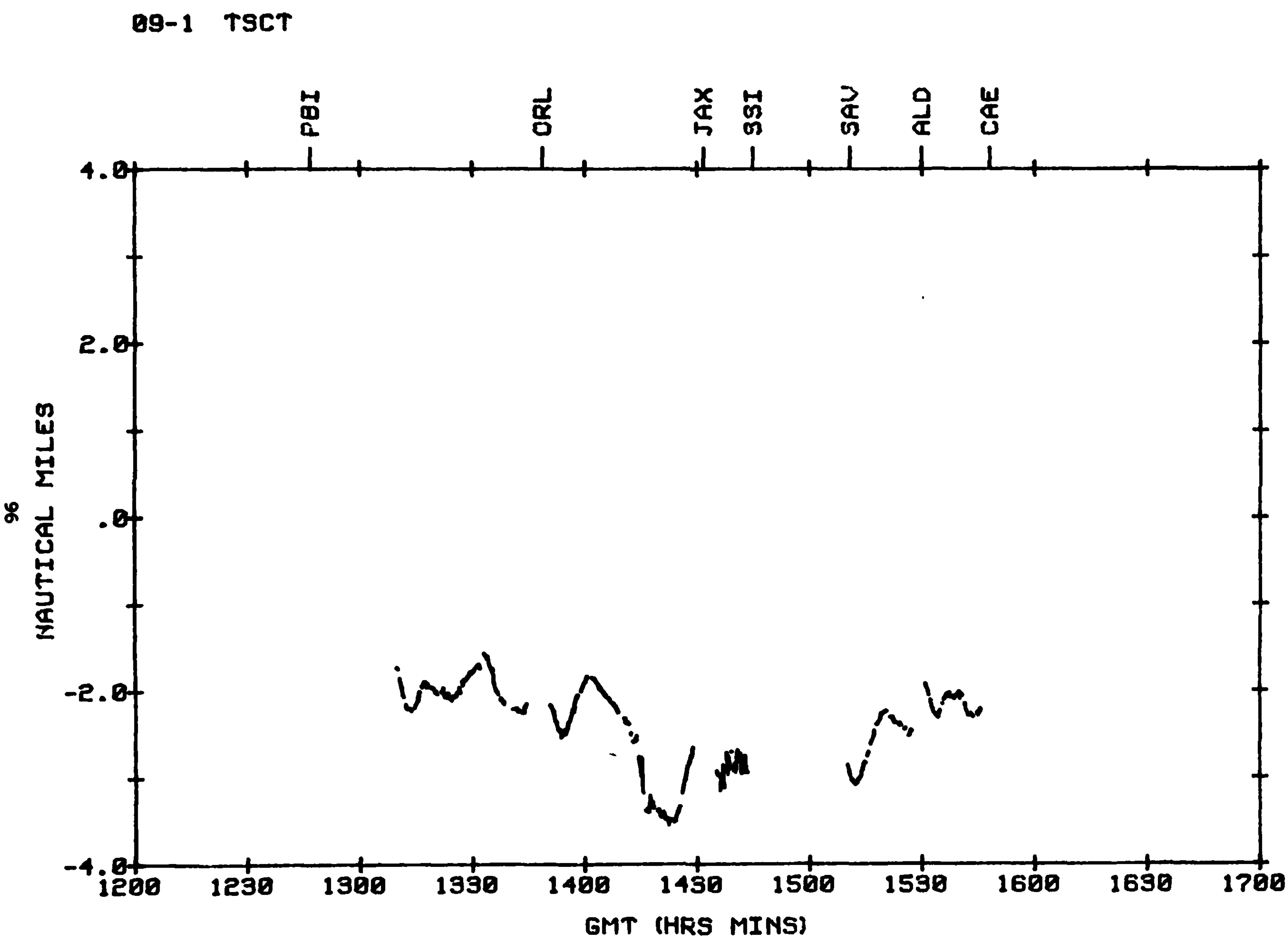


Figure B.15 Total System Crosstrack Error for Segment 1, Palm Beach, FL to Columbia, SC (May 9, 1983)

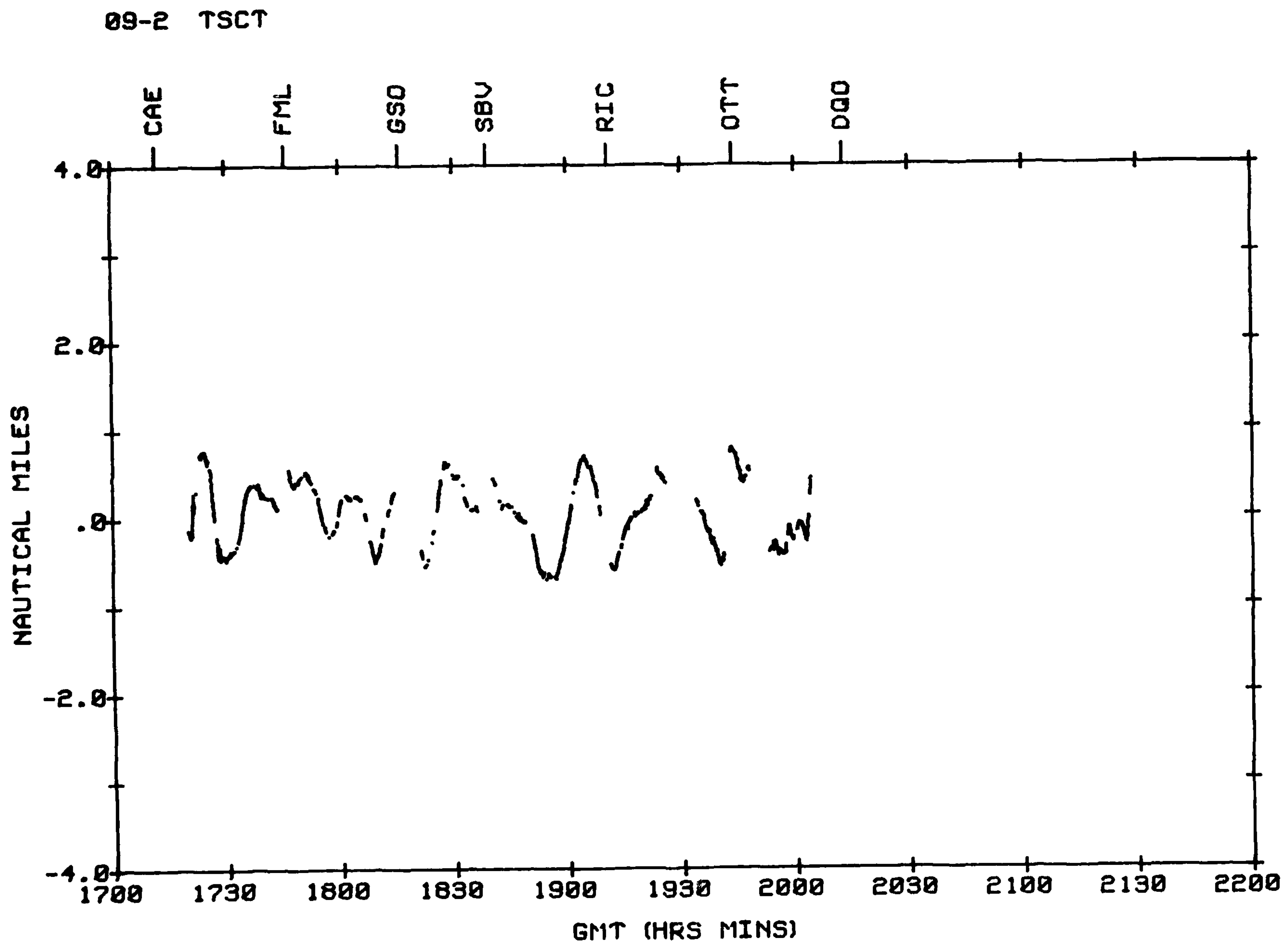


Figure B.16 Total System Crosstrack Error for Segment 2, Columbia, SC to Wilmington, DE (May 9, 1983)

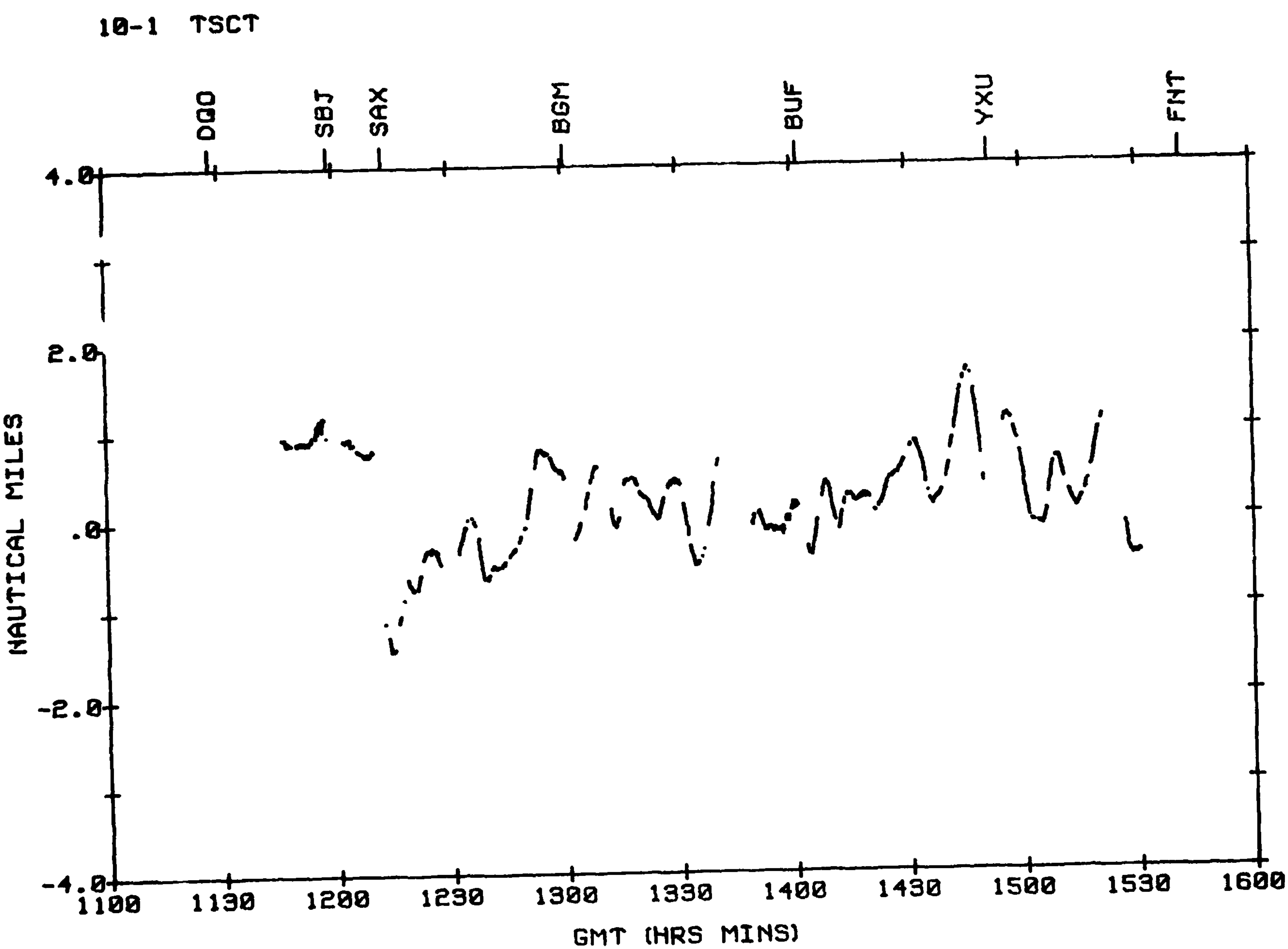


Figure B.17 Total System Crosstrack Error for Segment 3, Wilmington, DE to Flint, MI (May 10, 1983)

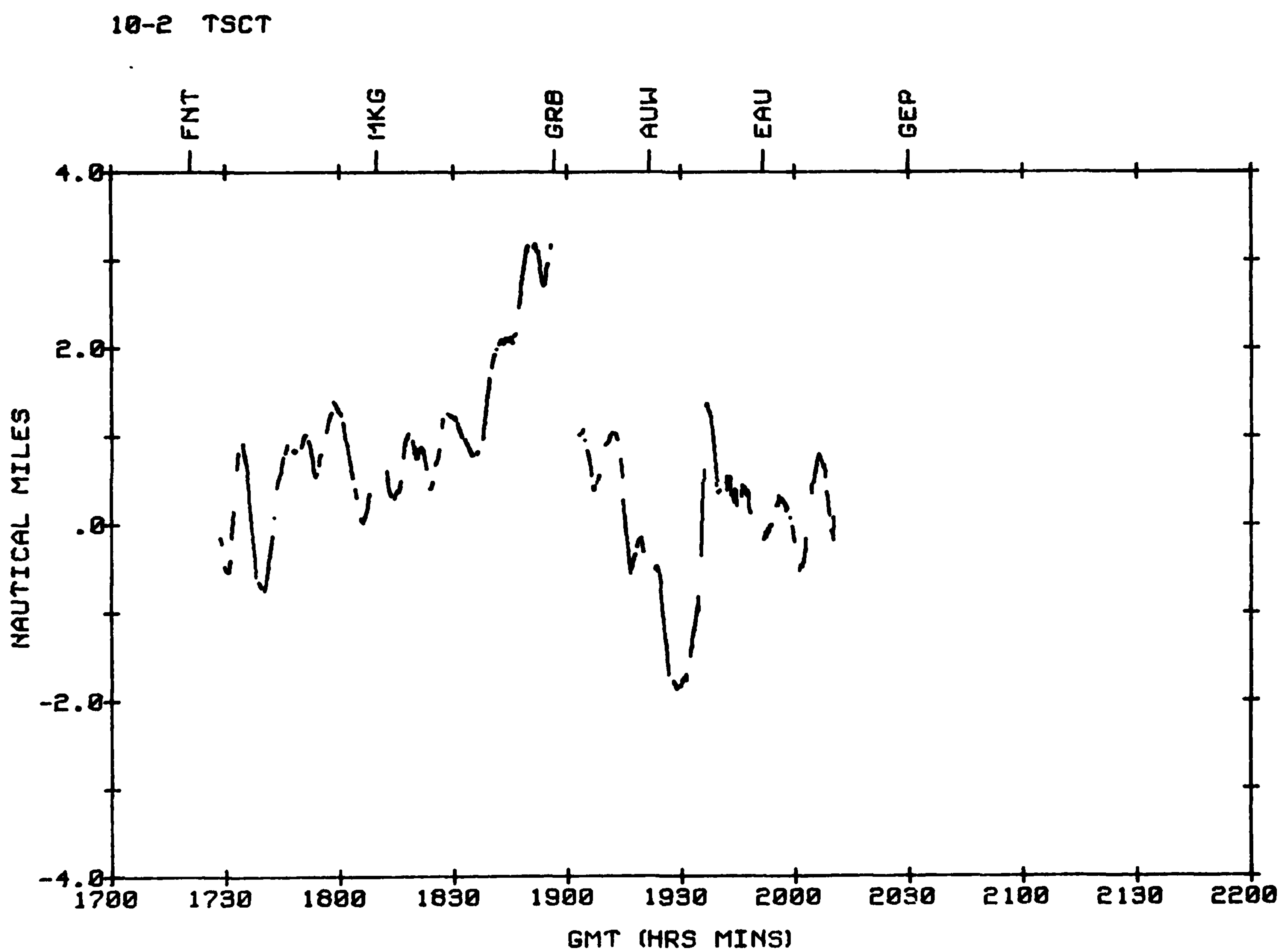


Figure B.18 Total System Crosstrack Error for Segment 4, Flint, MI to St. Paul, MN (May 10, 1983)

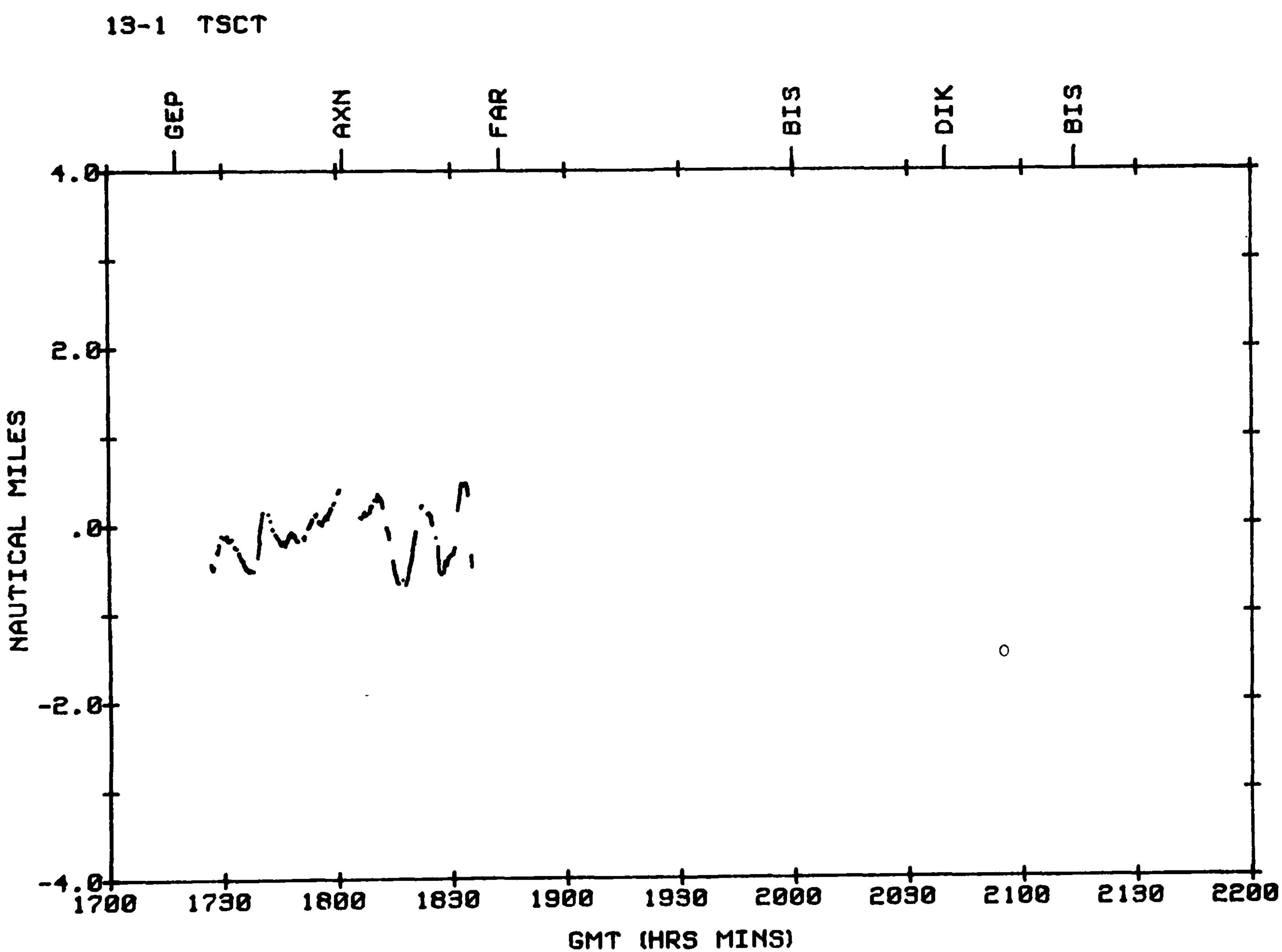


Figure B.19 Total System Crosstrack Error for Segment 5, St. Paul, MN to Bismarck, ND (May 13, 1983)

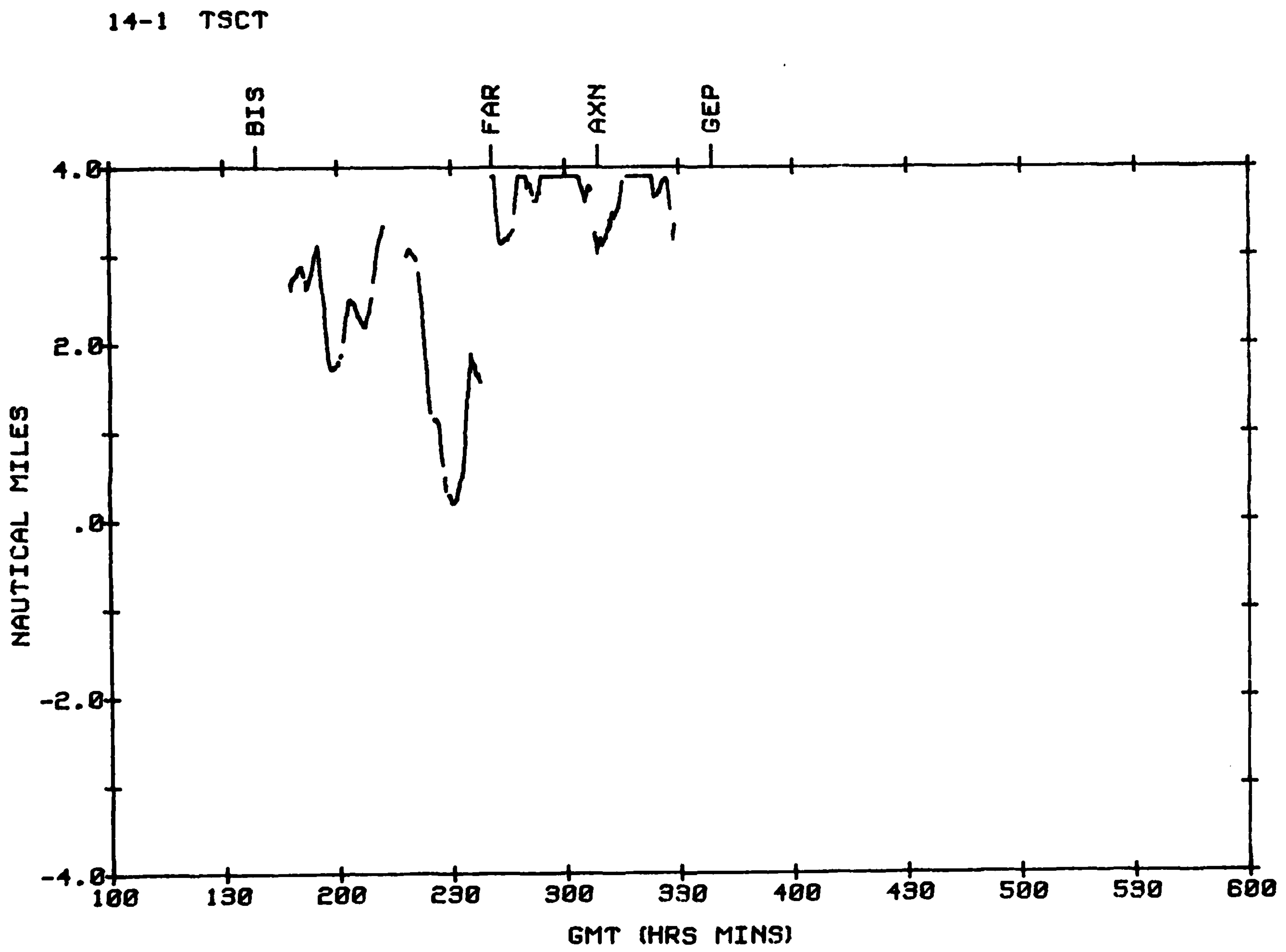


Figure B.20 Total System Crosstrack Error for Segment 6, Bismarck, ND to St. Paul, MN (May 14, 1983)

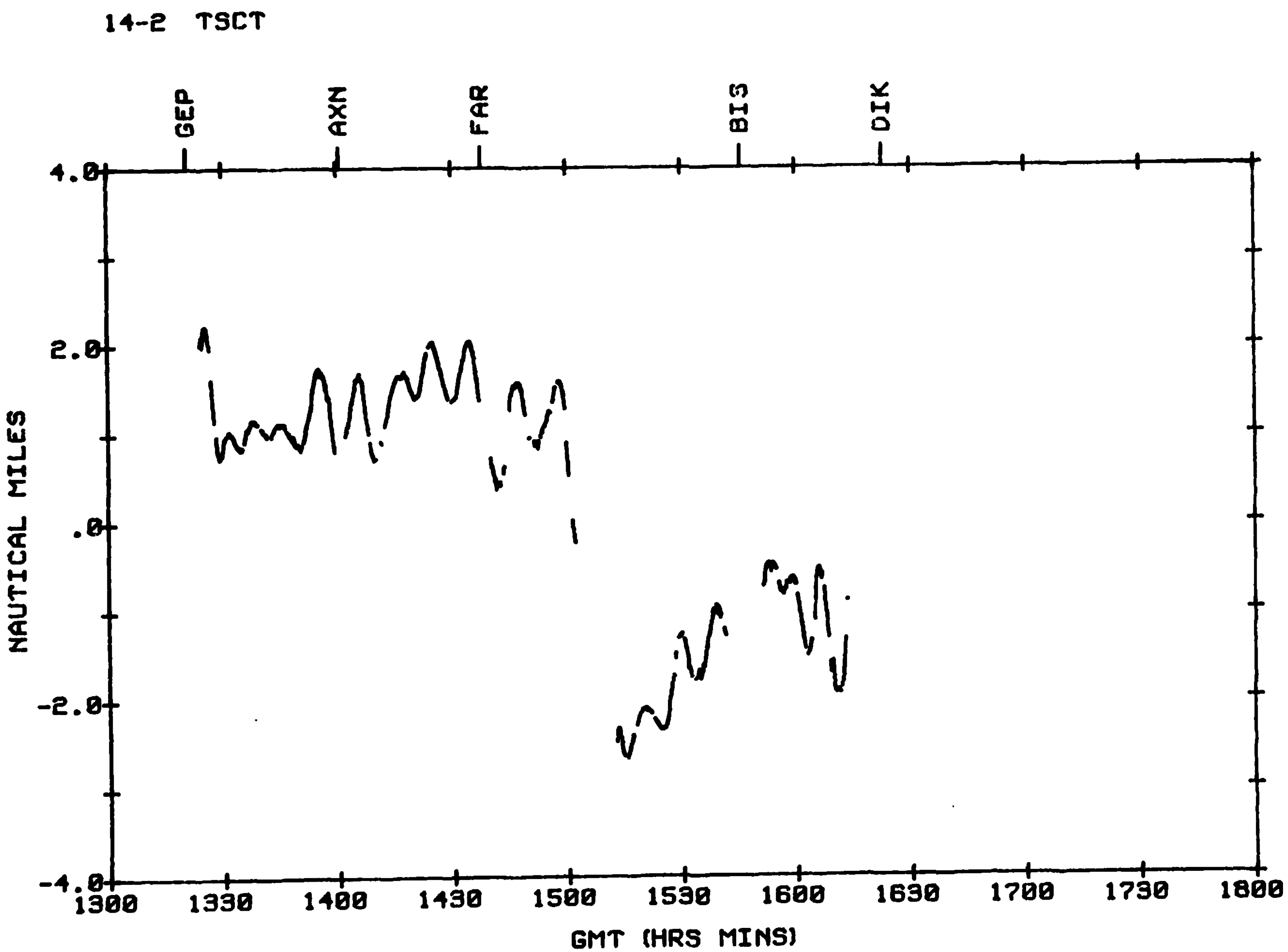


Figure B.21 Total System Crosstrack Error for Segment 7, St. Paul, MN to Dickinson, ND (May 14, 1983)

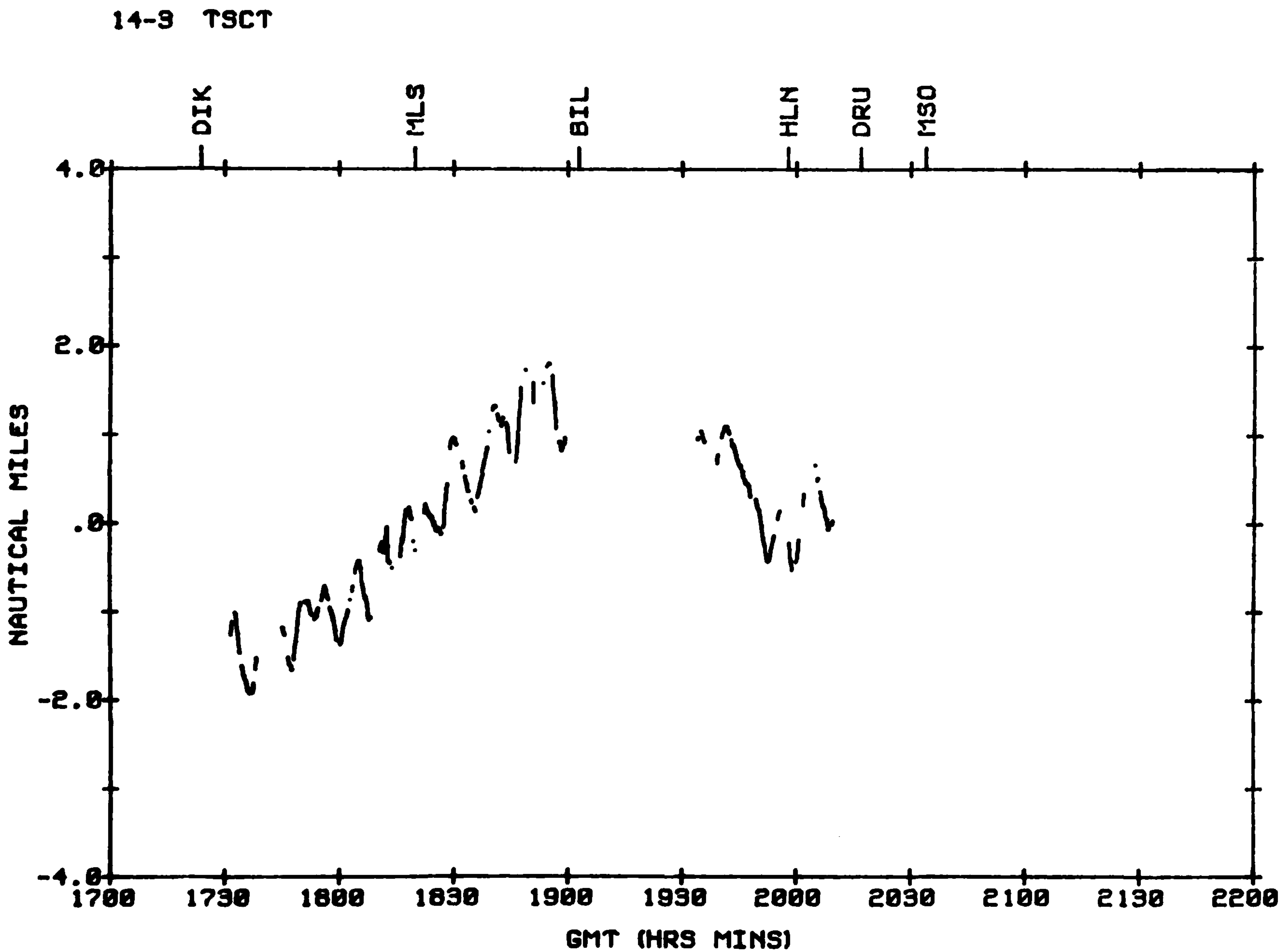


Figure B.22 Total System Crosstrack Error for Segment 8, Dickinson, ND to Missoula, MT (May 14, 1983)

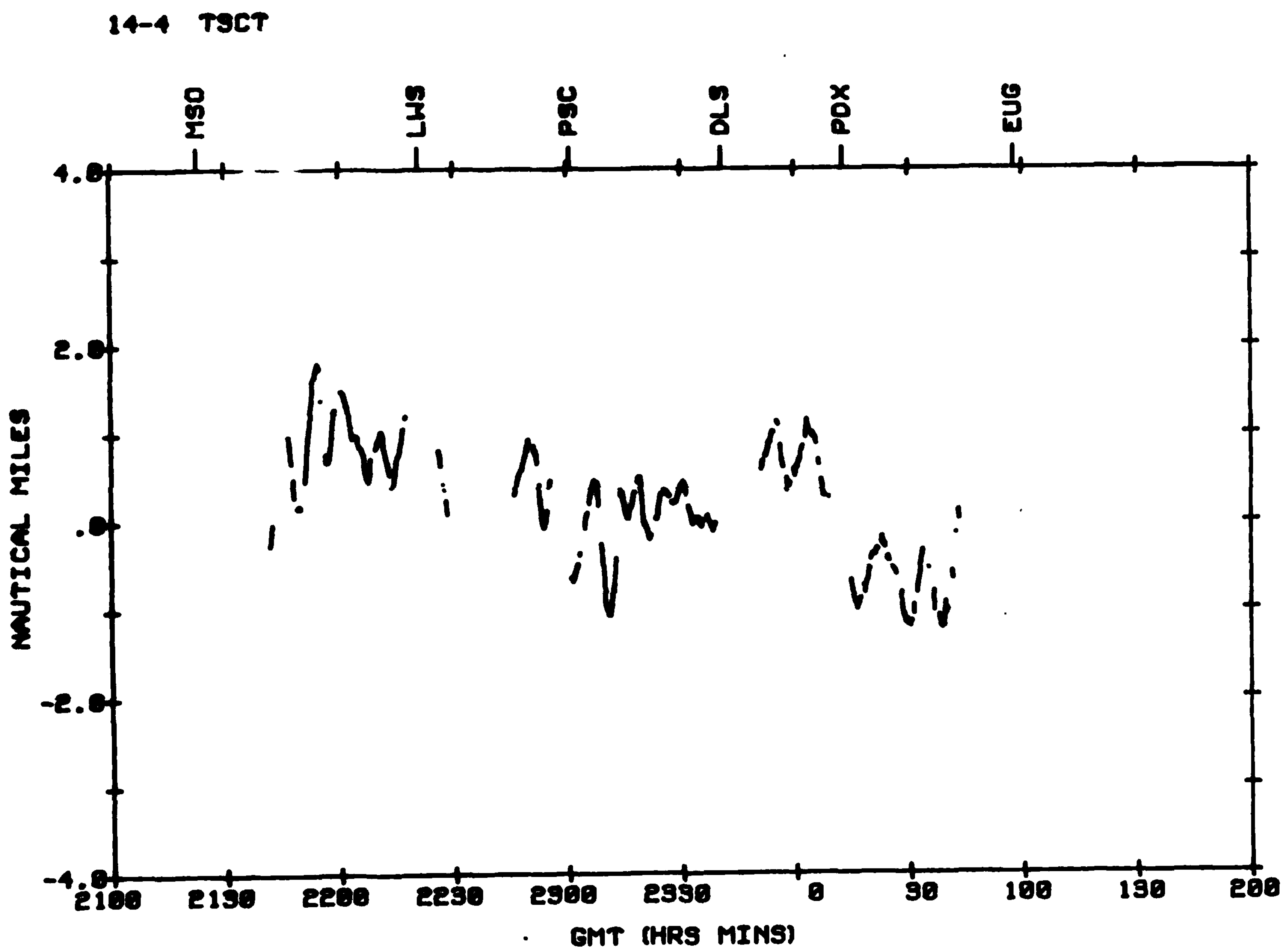


Figure B.23 Total System Crosstrack Error for Segment 9, Missoula, MT to Eugene, OR (May 14, 1983)

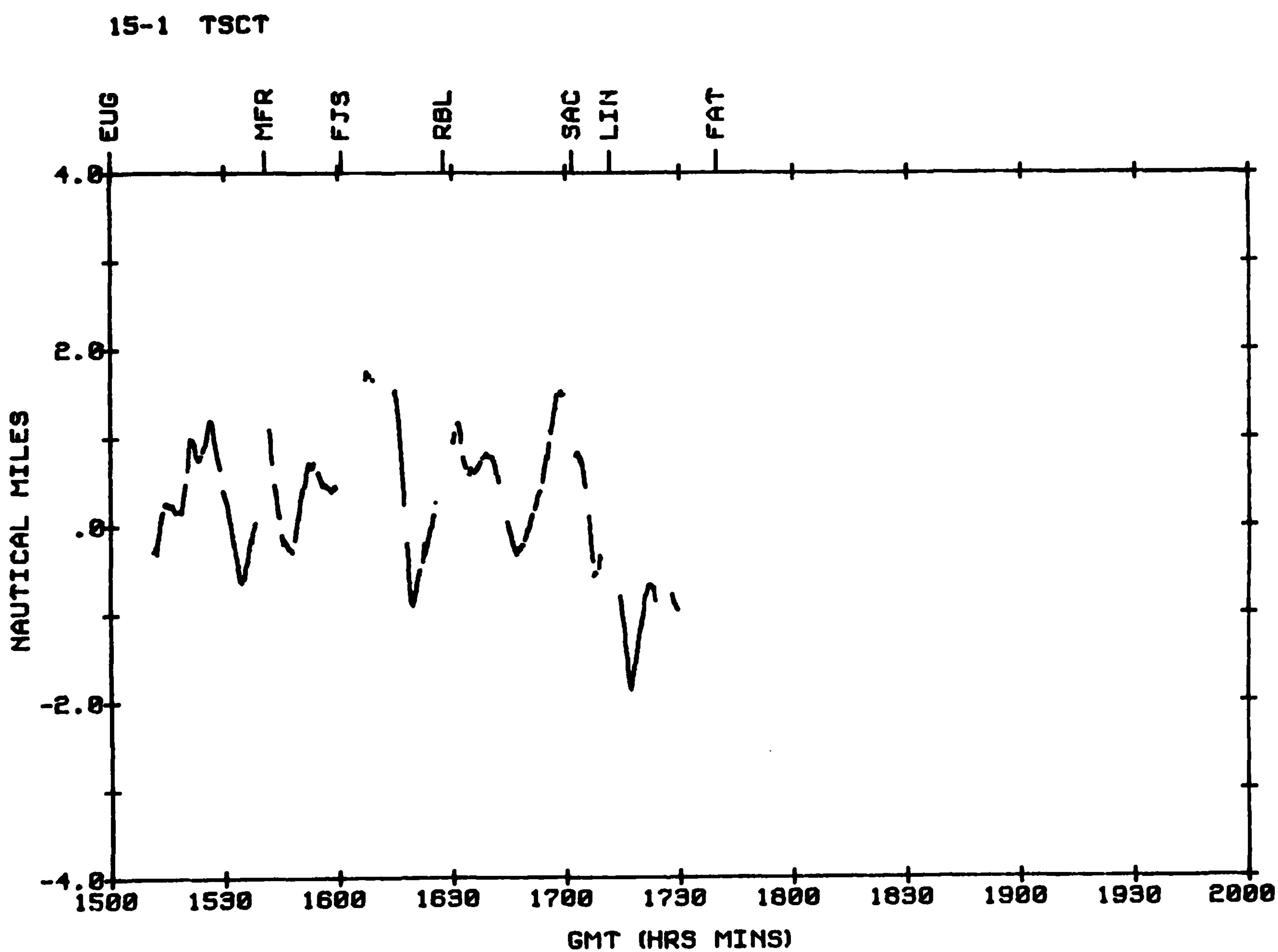


Figure B.24 Total System Crosstrack Error for Segment 10, Eugene, OR to Fresno, CA (May 15, 1983)

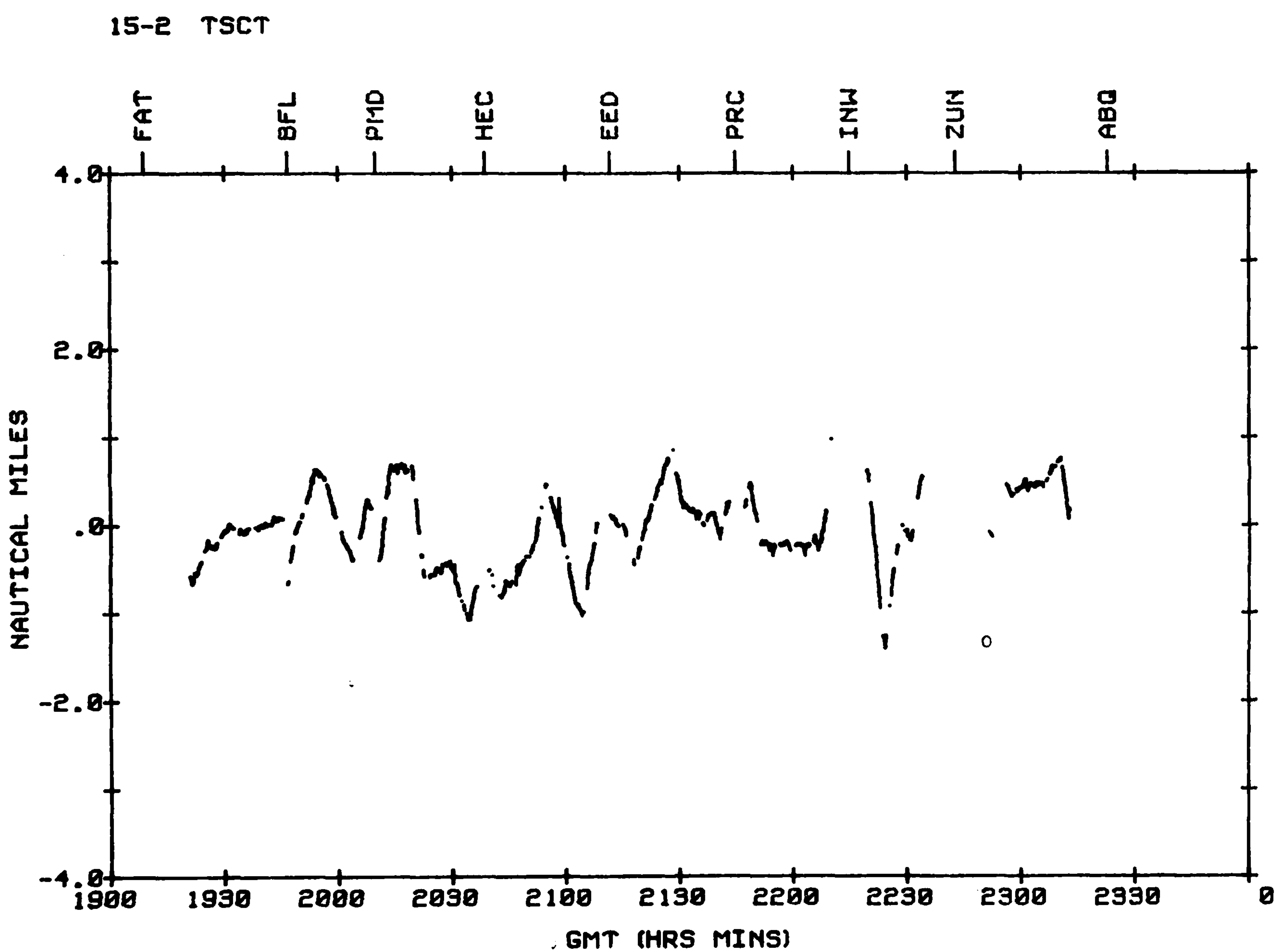


Figure B.25 Total System Crosstrack Error for Segment 11, Fresno, CA to Albuquerque, NM (May 15, 1983)

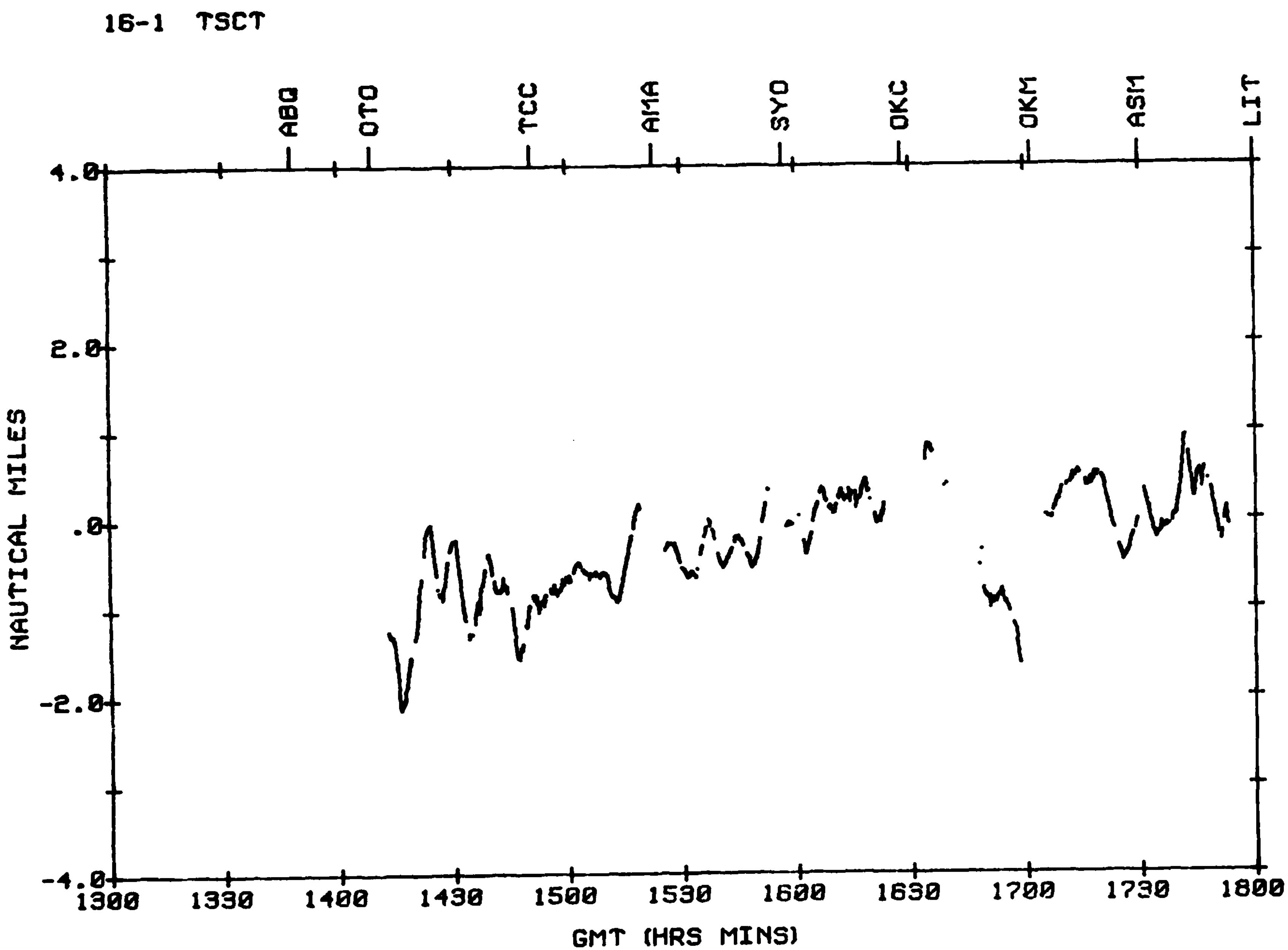


Figure B.26 Total System Crosstrack Error for Sement 12, Albuquerque, NM to Little Rock, AR (May 16, 1983)

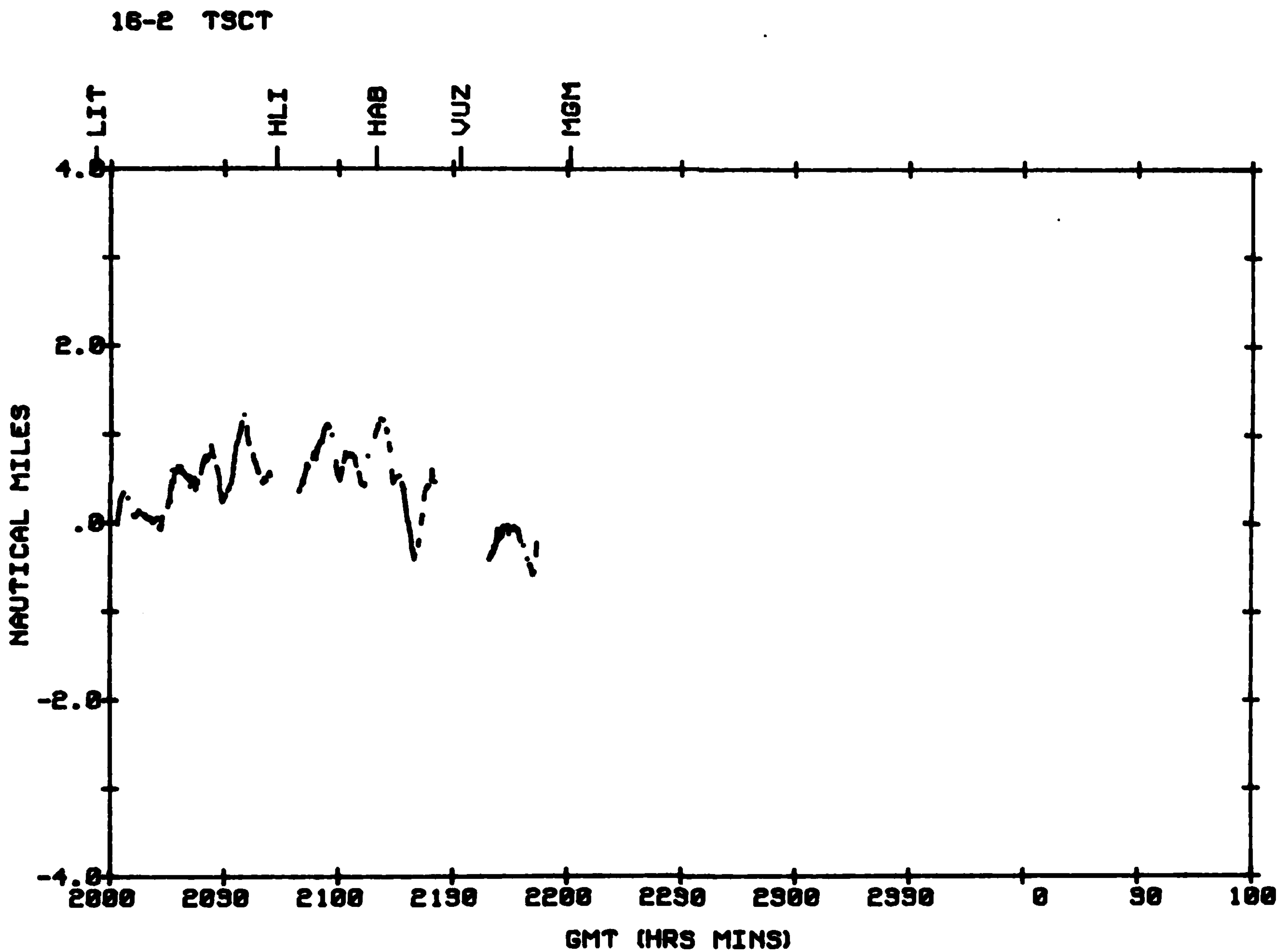


Figure B.27 Total System Crosstrack Error for Segment 13, Little Rock, AR to Montgomery, AL (May 16, 1983)

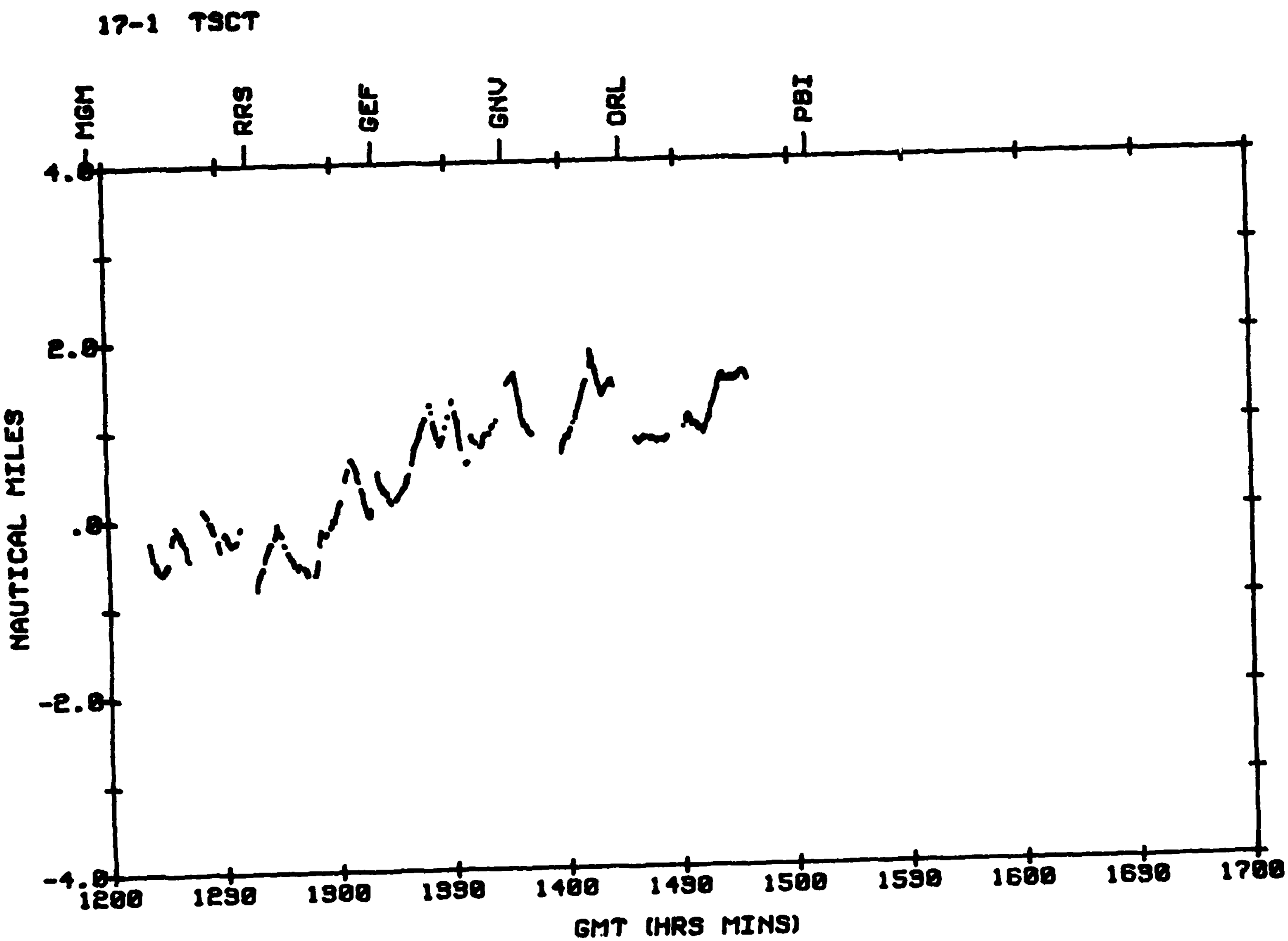


Figure B.28 Total System Crosstrack Error for Segment 14, Montgomery, AL to Palm Beach, FL (May 17, 1983)

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